

Time-domain astronomy

Sylvia J. Zhu

DESY Zeuthen

sylvia.zhu@desy.de

[she/her]



Rough outline

Day 1: Intro + detectors

How are gamma rays produced and how do we detect them?

Day 2: Rapid transients

How do IACTs observe gamma-ray bursts and other rapidly fading transients?

Day 3: Longer duration transients

What else must be considered for longer duration transients like supernovae?

Rough outline

Day 1: Intro + detectors

How are gamma rays produced and how do we detect them?

Day 2: Rapid transients

How do IACTs observe gamma-ray bursts and other rapidly fading transients?

Day 3: Longer duration transients

What else must be considered for longer duration transients like supernovae?

Day 2a: Observational

Day 2b: Phenomenological

Part 2b. Gamma-ray bursts and related phenomena

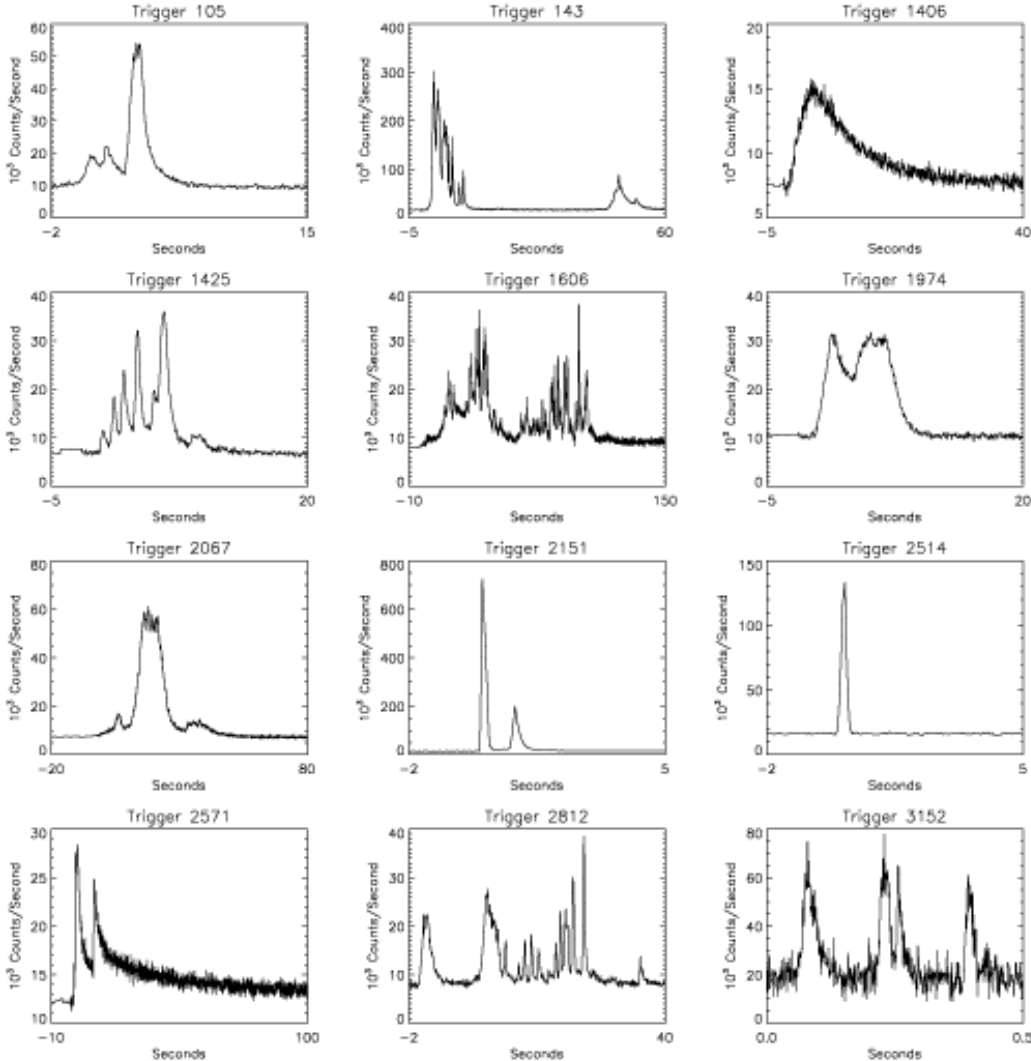
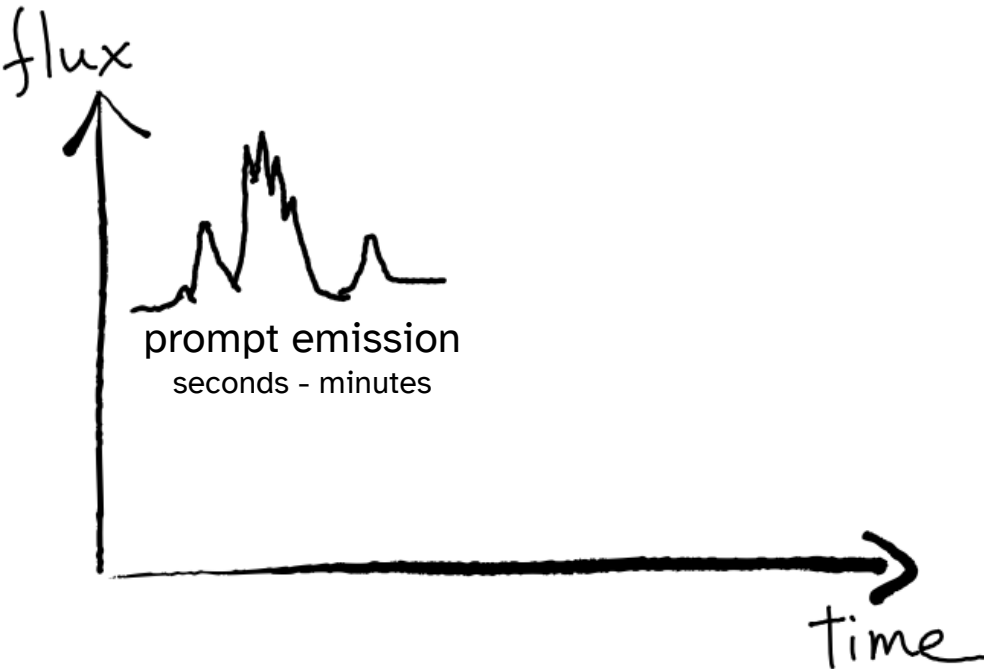
MORE ABOUT GAMMA-RAY BURSTS HOORAY

disclaimer: This is from a data analyst POV!
All the theory will be vastly simplified!!!
and some of it might be incorrect ...



Gamma-ray bursts

What causes them?

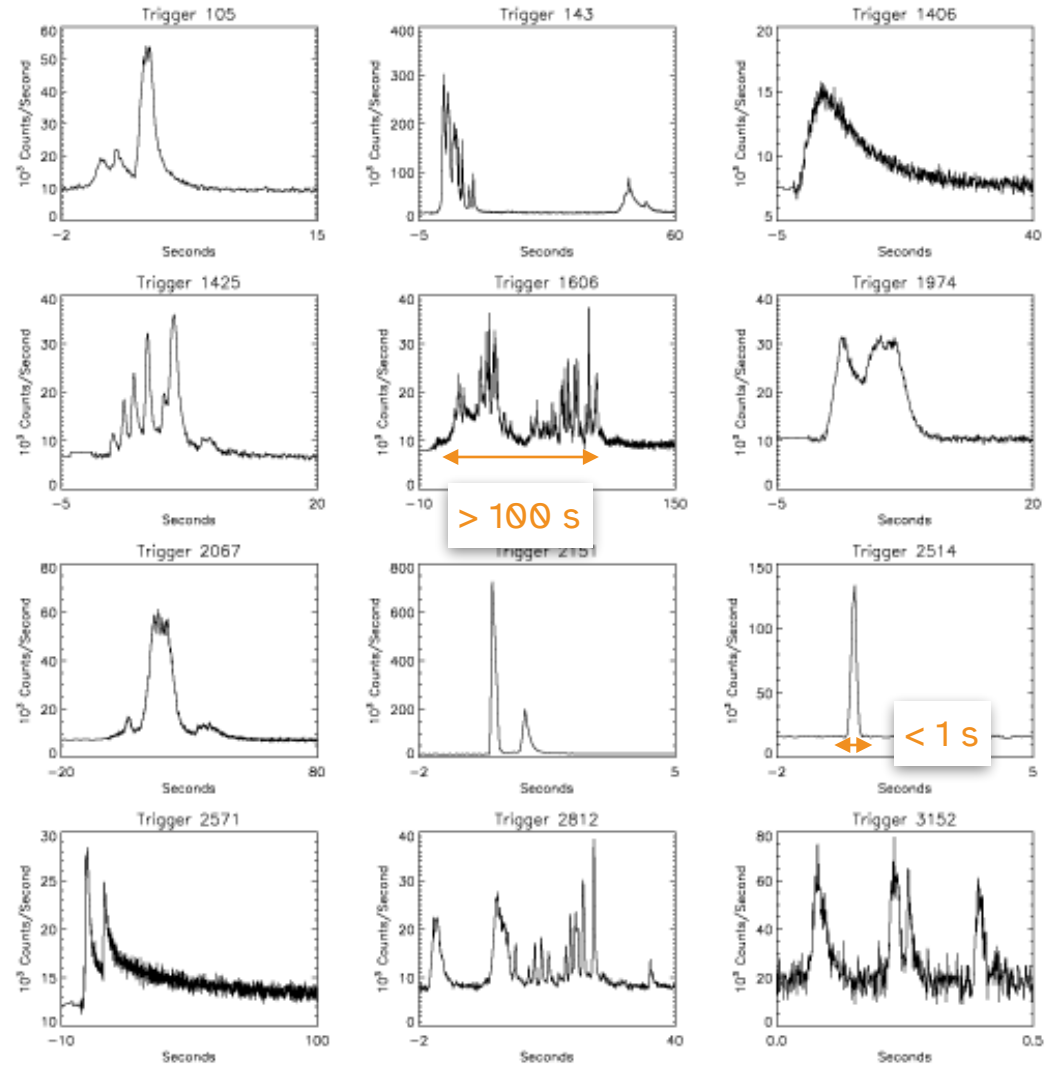
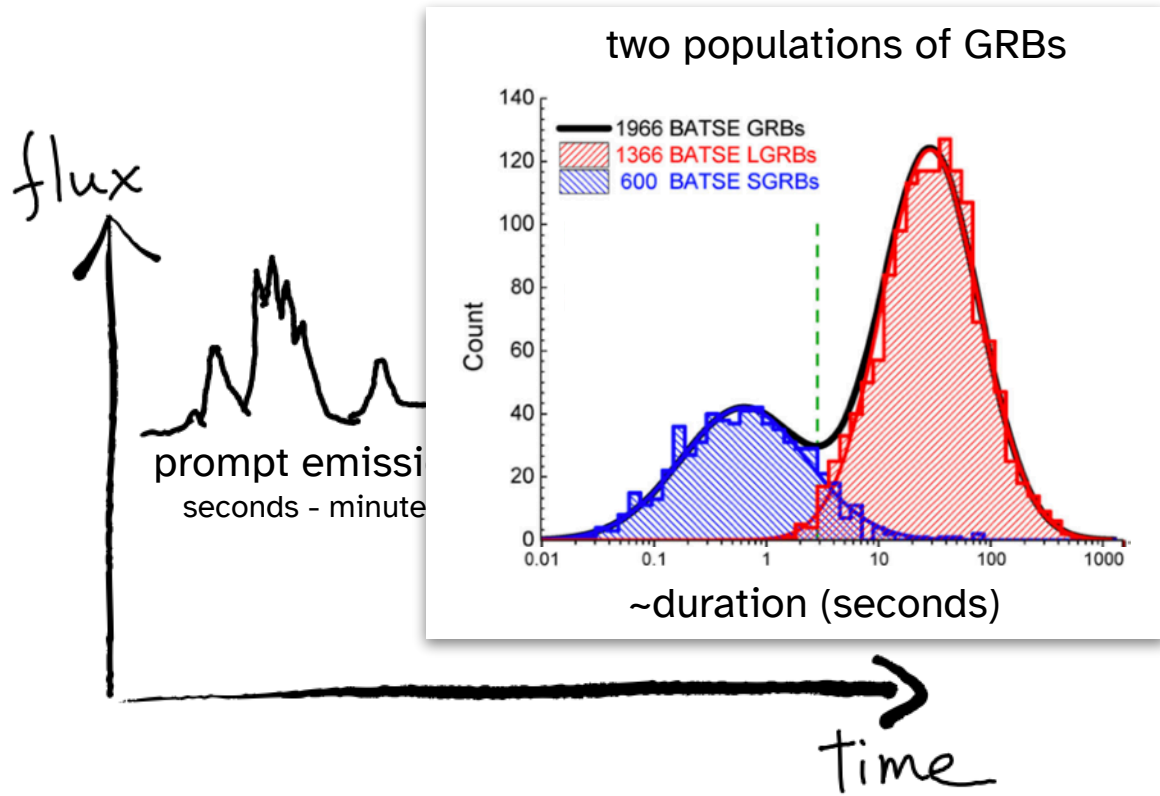


[J. T. Bonnell (NASA/GSFC)]

Gamma-ray bursts

What causes them?

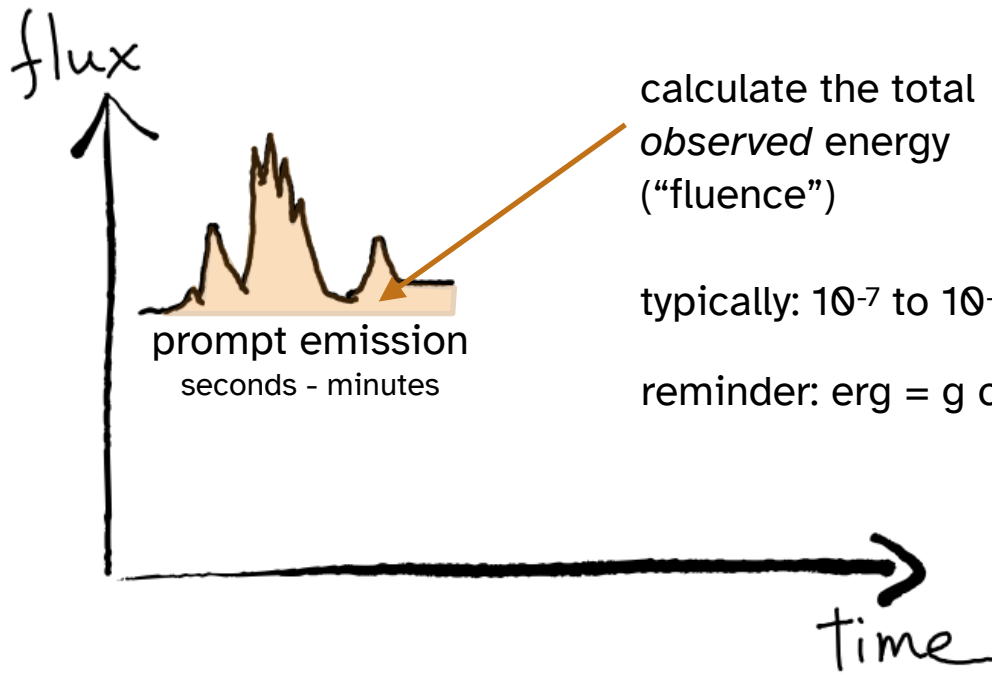
[A. Shahmoradi & R. J. Nemiroff, MNRAS 451 (2015)]



[J. T. Bonnell (NASA/GSFC)]

Gamma-ray bursts

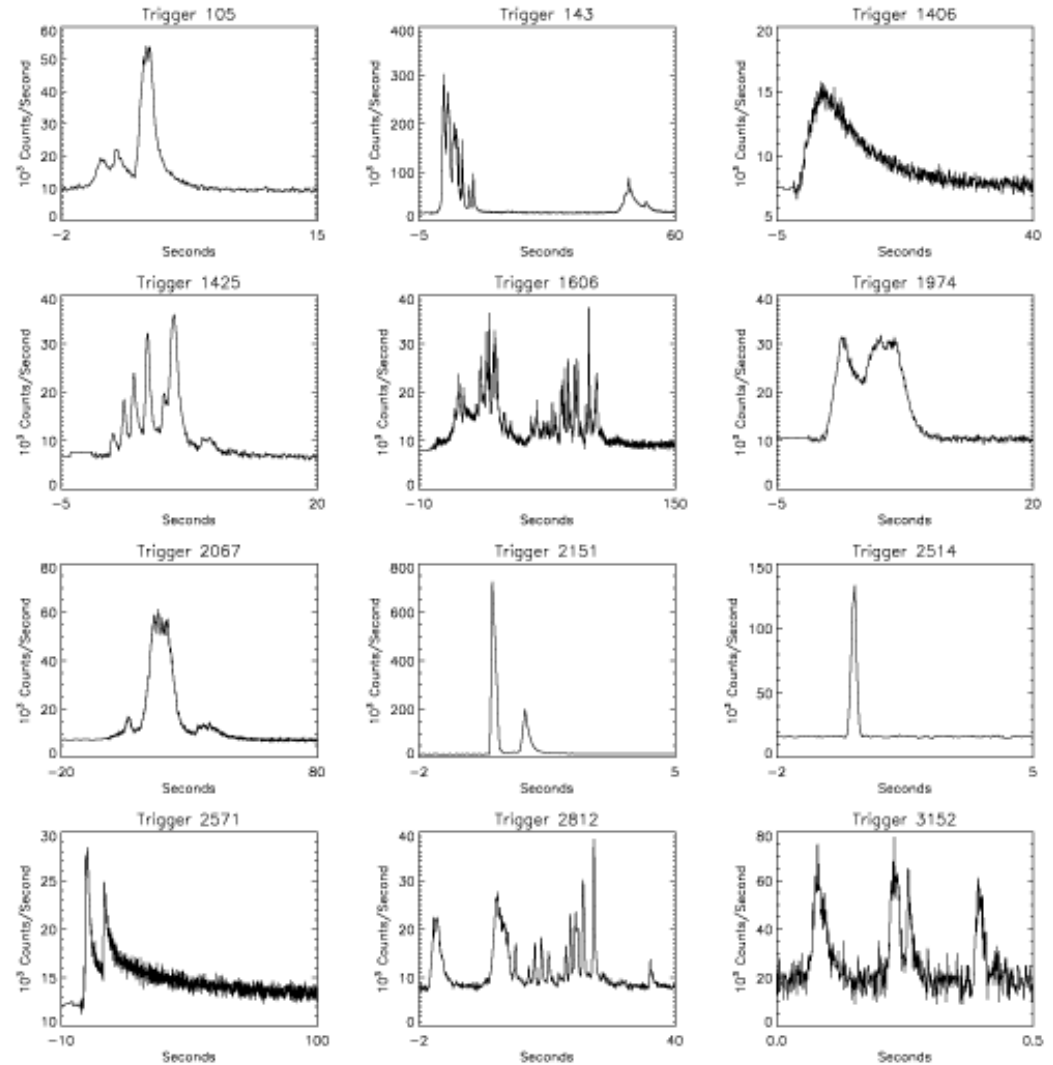
What causes them?



calculate the total observed energy ("fluence")

typically: 10^{-7} to 10^{-4} erg cm^{-2}

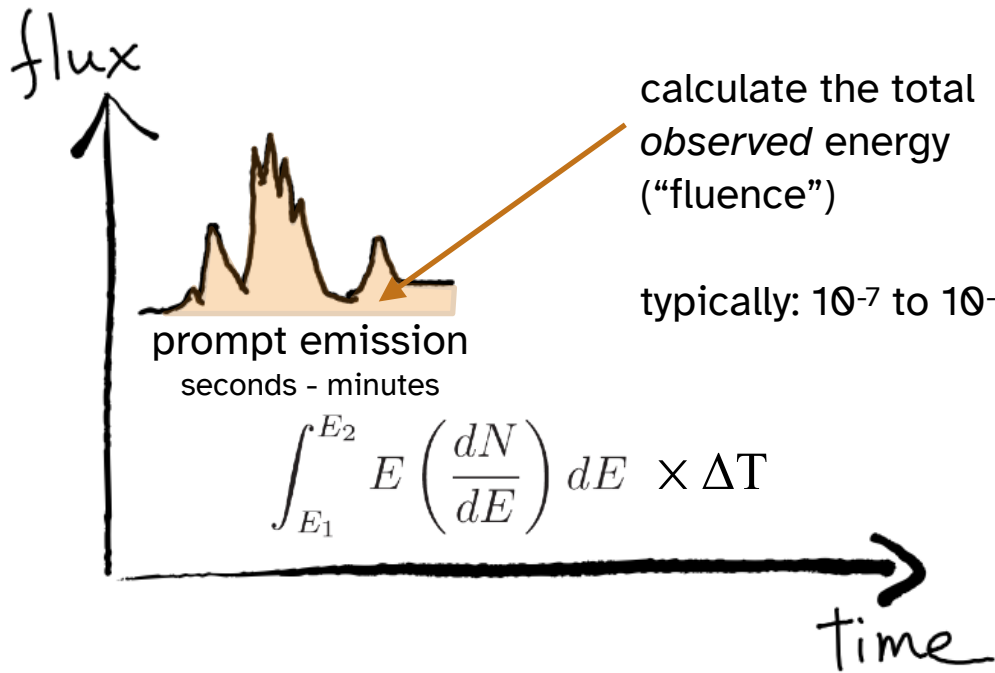
reminder: erg = g cm^2 s $^{-2}$



[J. T. Bonnell (NASA/GSFC)]

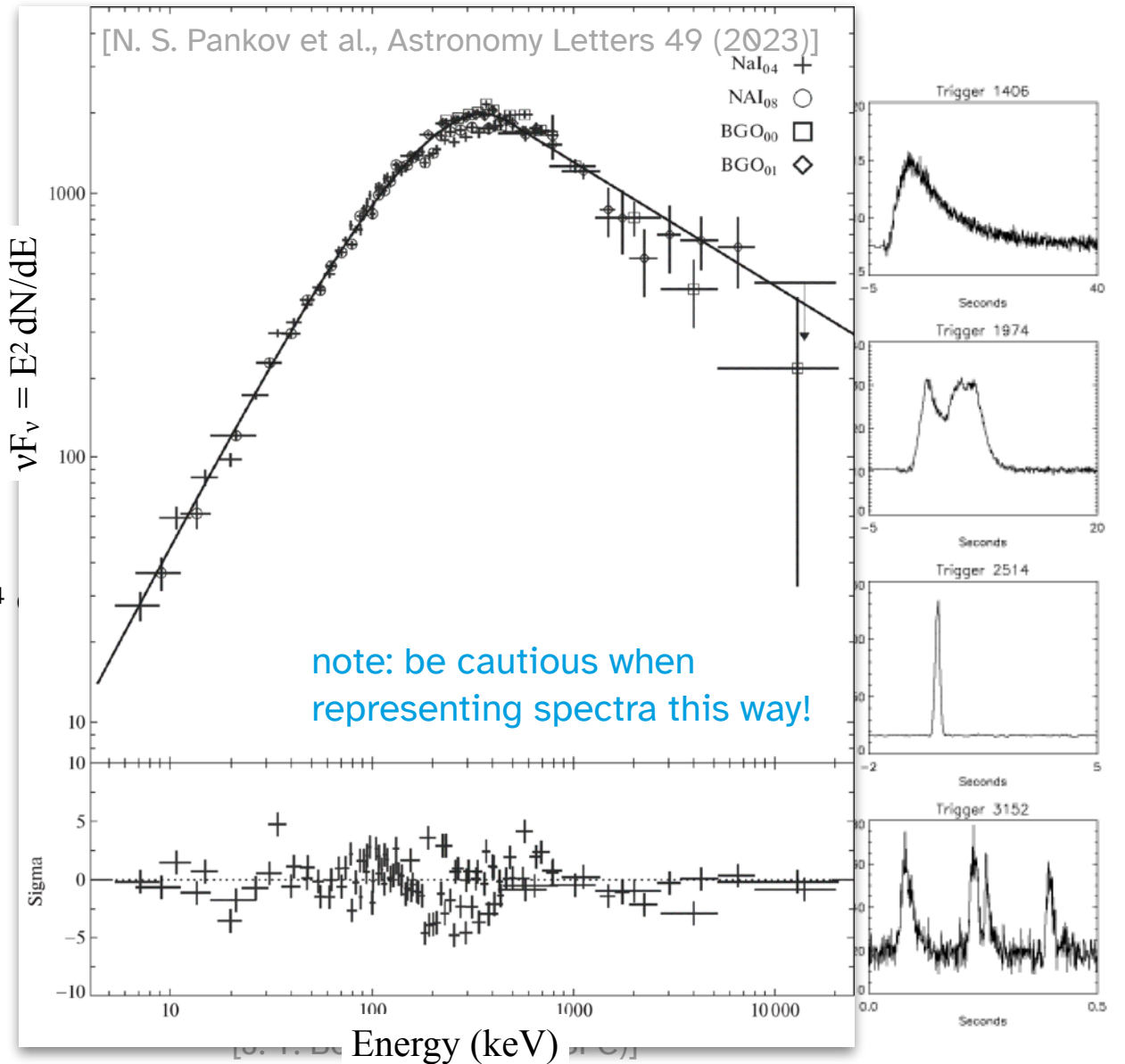
Gamma-ray bursts

What causes them?



calculate the total observed energy ("fluence")

typically: 10^{-7} to 10^{-4}



Gamma-ray bursts

What causes them?

[N. S. Pankov et al., Astronomy Letters 49 (2023)]

NaI₀₄ +

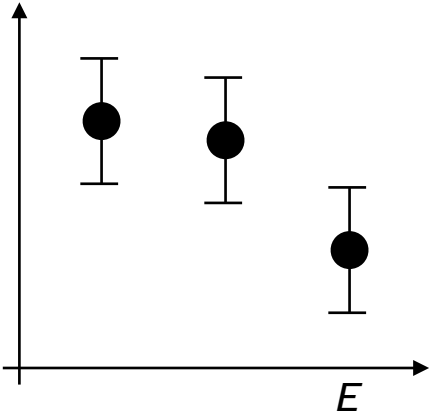
NaI₀₈ ○

BGO₀₀ □

Trigger 1406

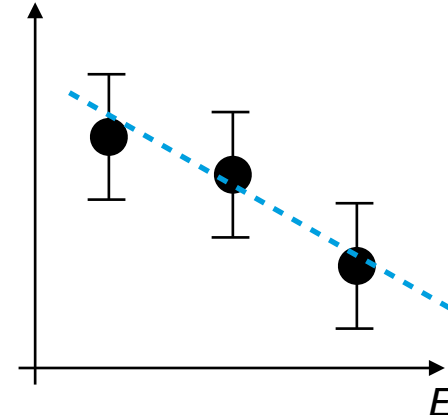
flu

observed counts

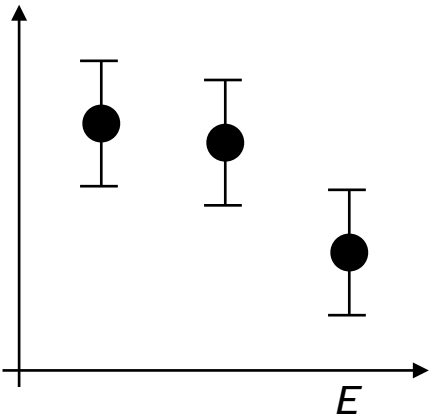


assume power-law spectrum

$E^2 dN/dE$

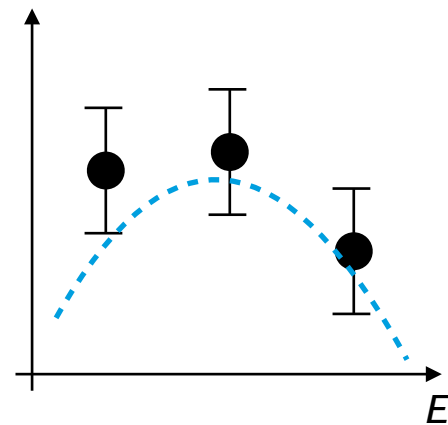


observed counts



assume log-parabola spectrum

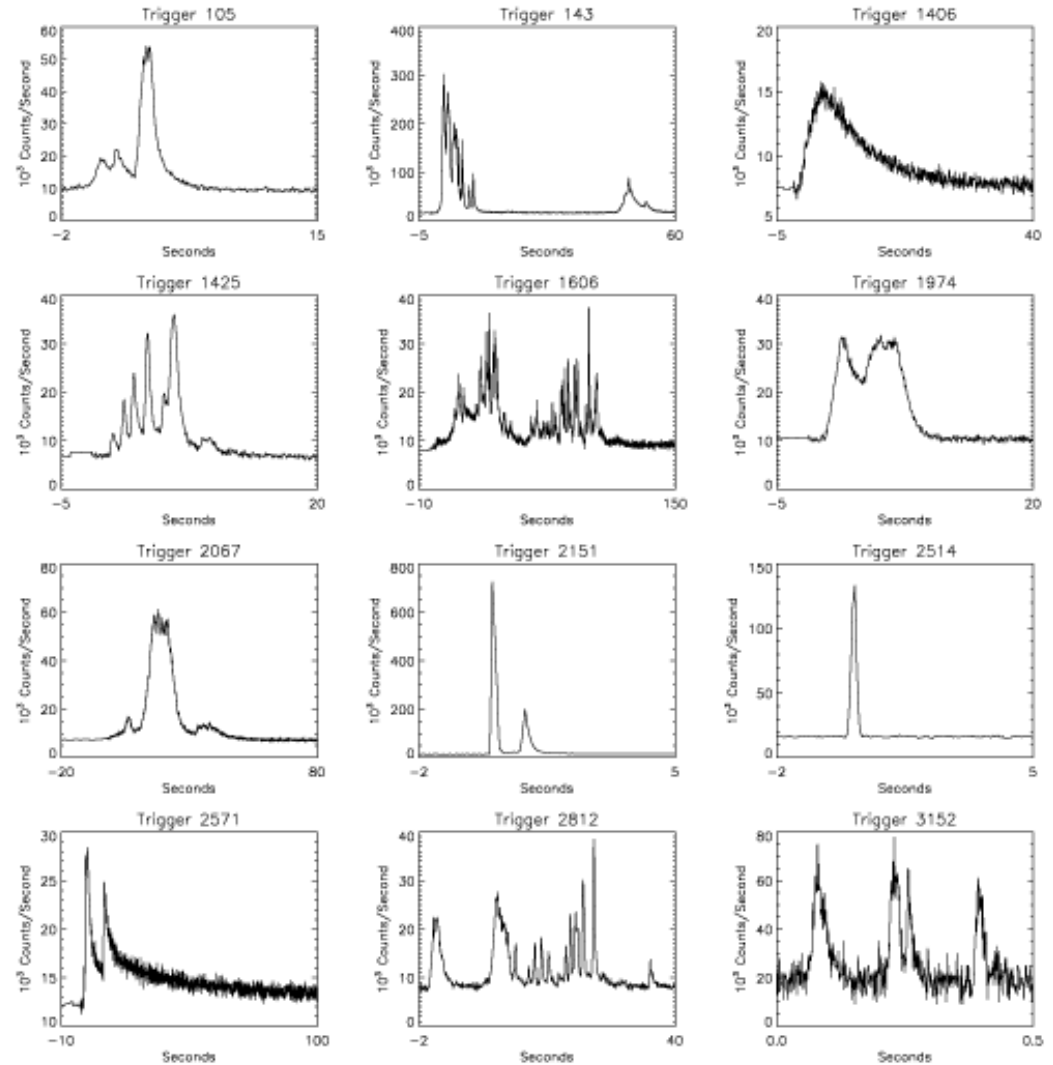
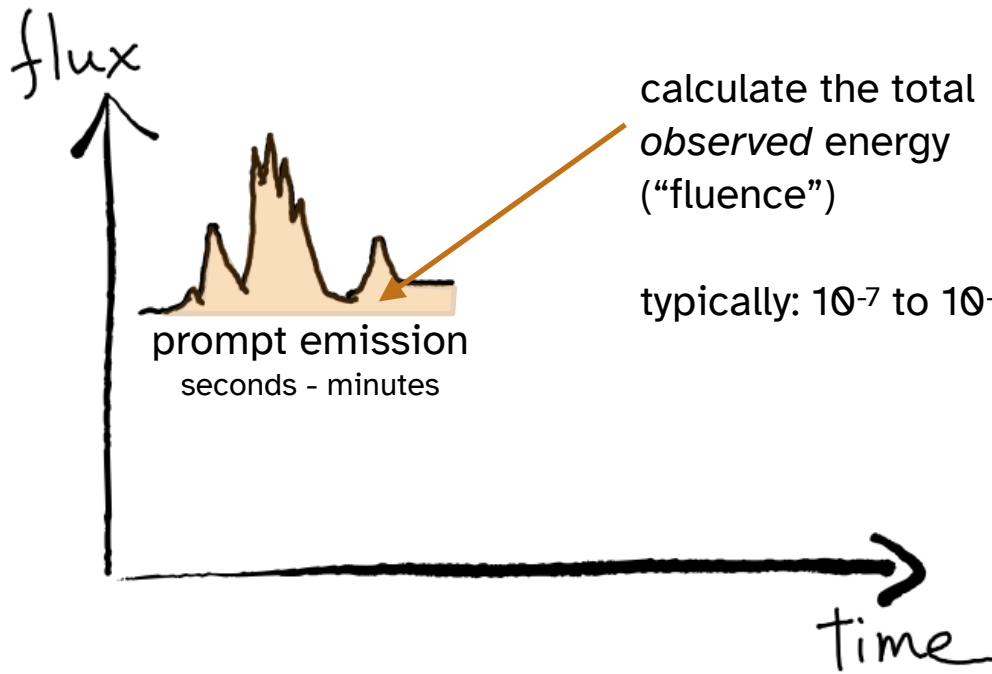
$E^2 dN/dE$



two very different spectra!!
=> if you change your underlying model (e.g. you want to apply a specific theoretical model), you should **refit the data**

Gamma-ray bursts

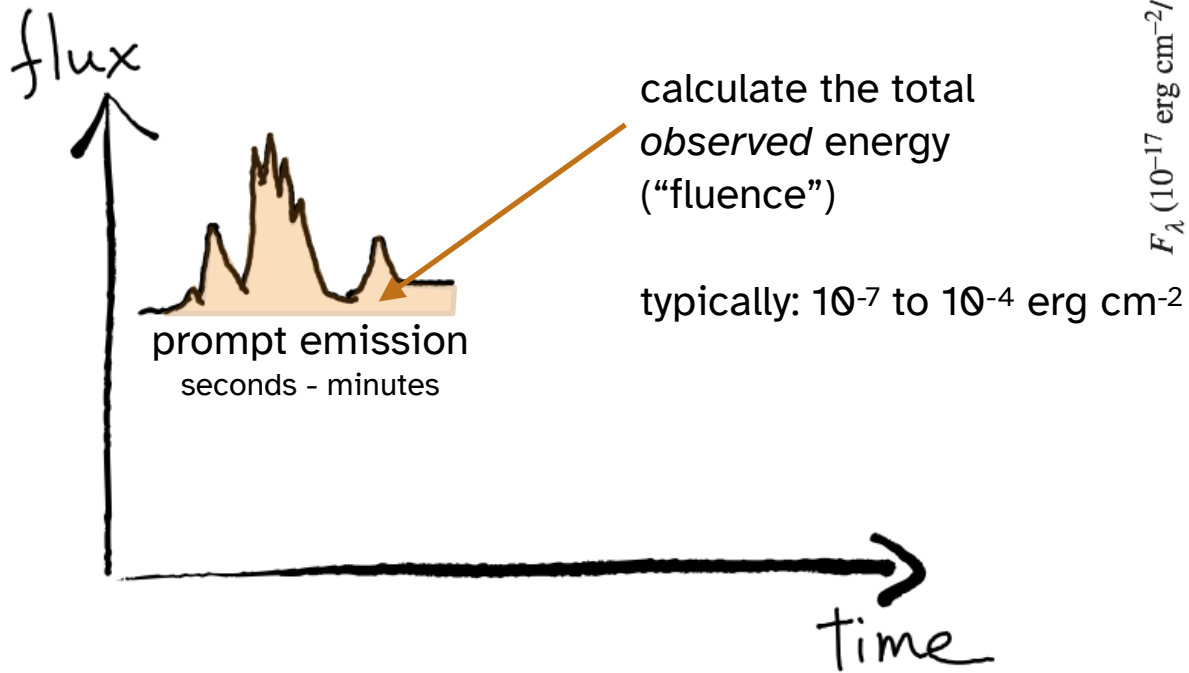
What causes them?



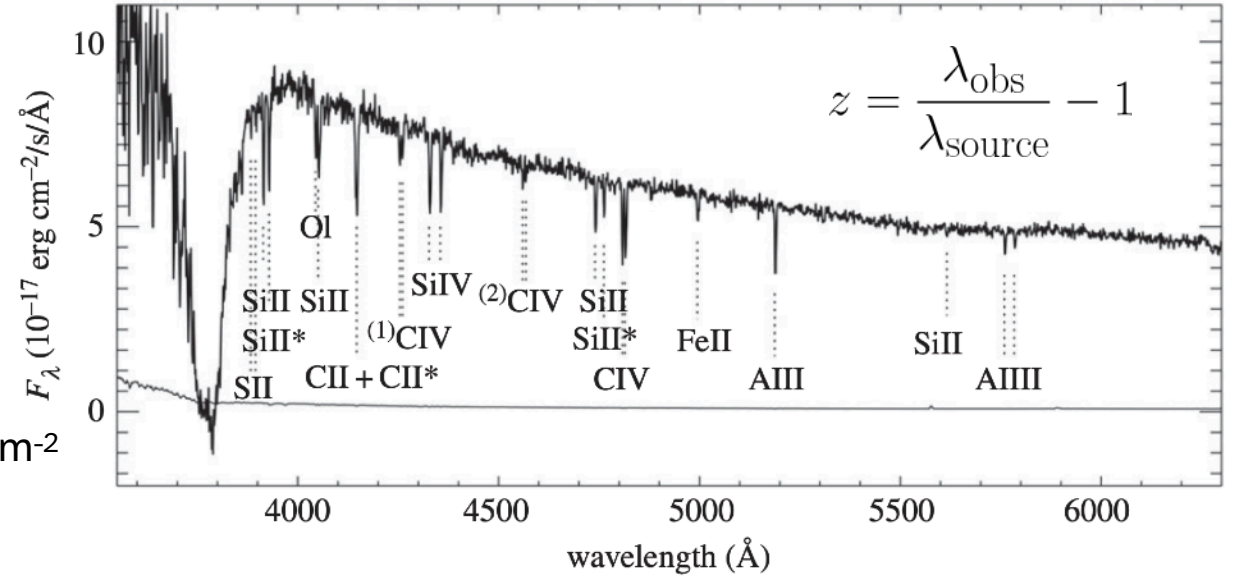
[J. T. Bonnell (NASA/GSFC)]

Gamma-ray bursts

What causes them?



[A. Rau et al., ApJ 720 (2010)]



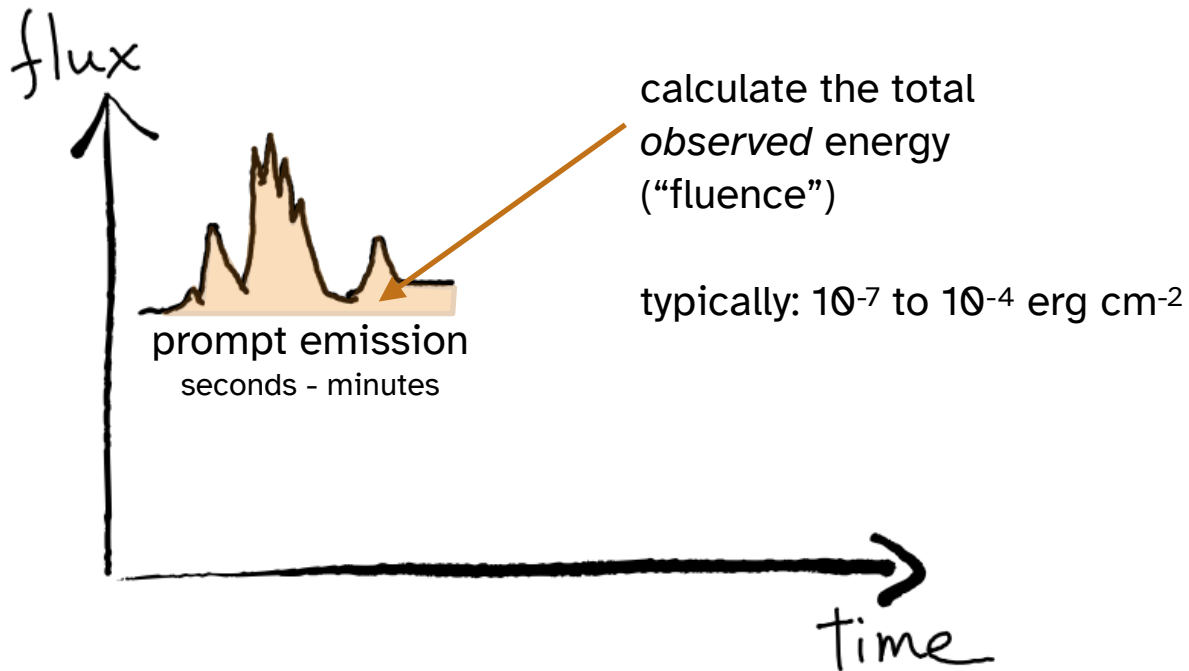
e.g., O I line: 4050 Å here } $z \sim 2$ ~ 16 Gpc
1356 Å rest frame

Very useful: [Cosmology Calculator]

BUT be careful about default cosmology values

Gamma-ray bursts

What causes them?



fluence S : 10^{-4} erg/cm 2

distance r : 16 Gpc

energy emitted by the source (assuming isotropic):

$$E_{\text{ISO}} = 4\pi r^2 S \sim 10^{54} \text{ erg}$$

by comparison, the rest energy of the Sun:

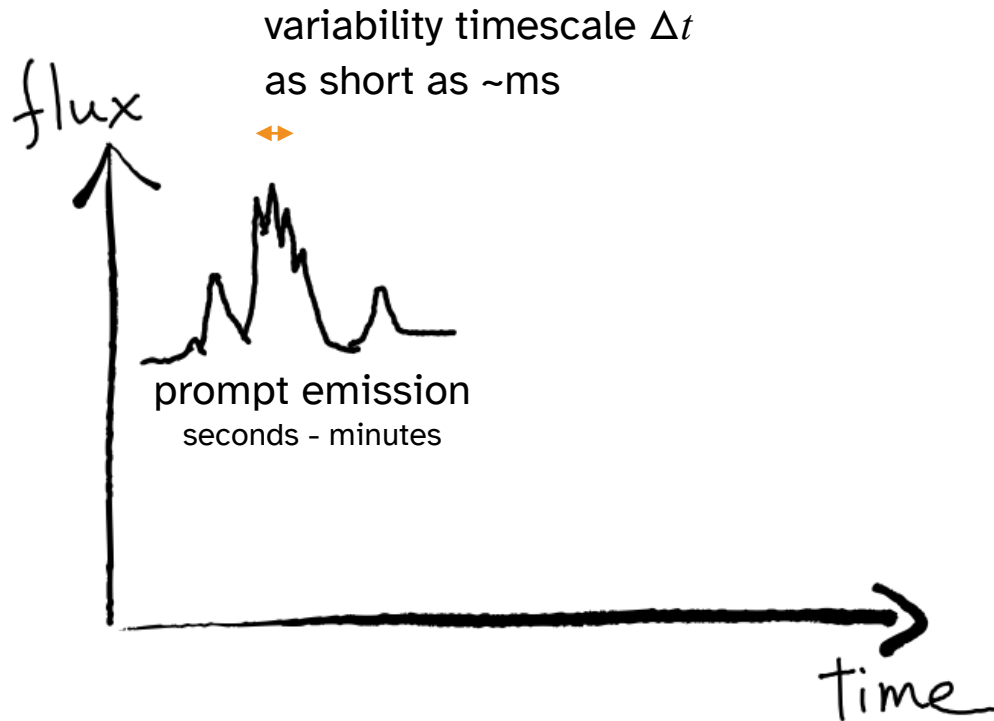
$$E_{\odot} = 10^{54} \text{ erg}$$

So: GRBs are stellar-sized phenomena (not, e.g., galaxy-sized or planet-sized)

release as much energy in minutes as the Sun will in its entire lifetime

Gamma-ray bursts

What causes them?



size of emitting region:

$$d = c\Delta t \sim 10^5 \text{ m}$$

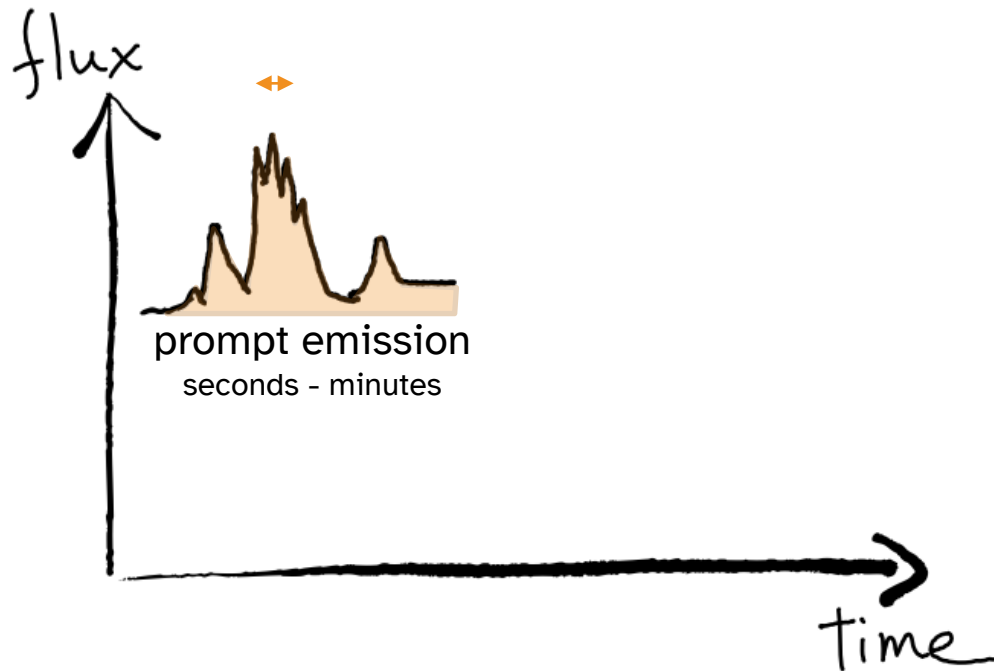
compare to the radius of Earth:

$$R_{\oplus} = 6 \times 10^6 \text{ m}$$

so, emission is occurring in regions smaller than the Earth

Gamma-ray bursts

What causes them?



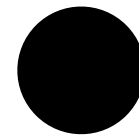
Combining these facts:

GRBs are stellar-sized phenomena

release $M_{\odot}c^2$ within minutes

emission occurring in regions smaller than the Earth

=> stellar-mass compact objects must be involved



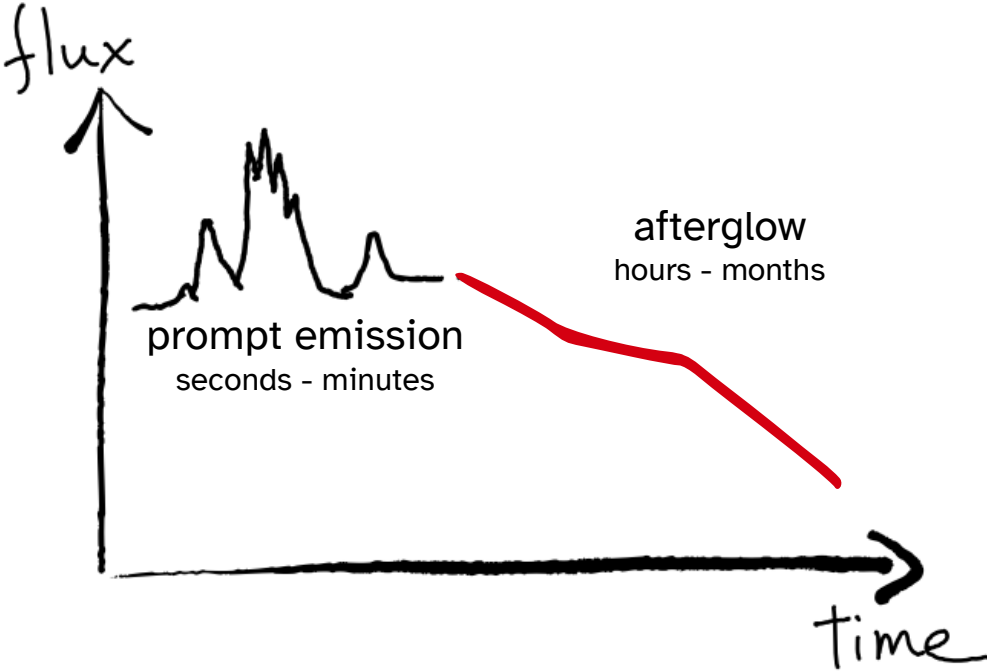
(stellar mass)
black
holes



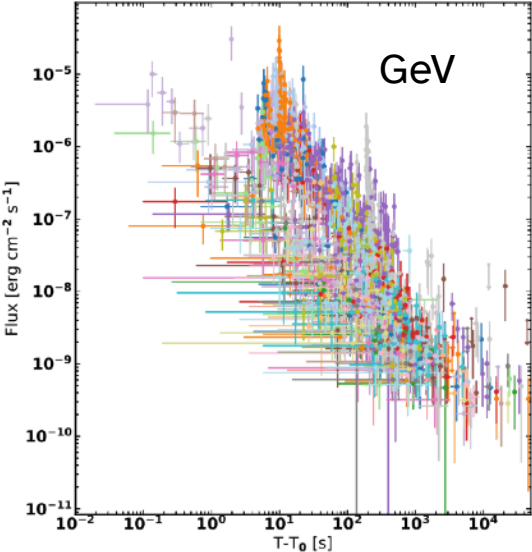
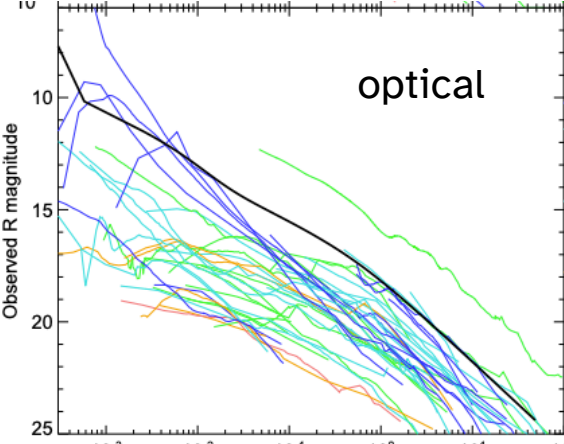
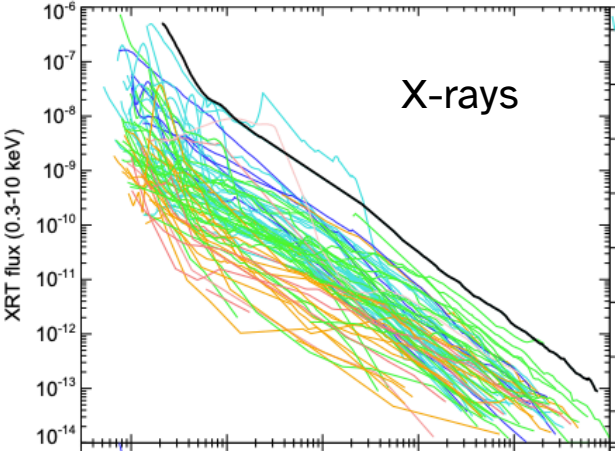
neutron
stars

Gamma-ray bursts

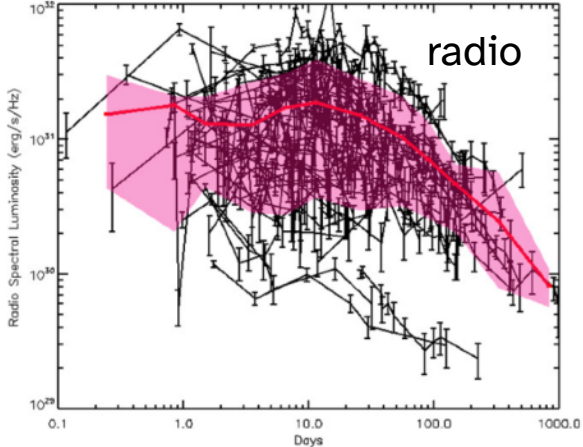
What causes them?



D. A. Perley et al., ApJ 781 (2014)



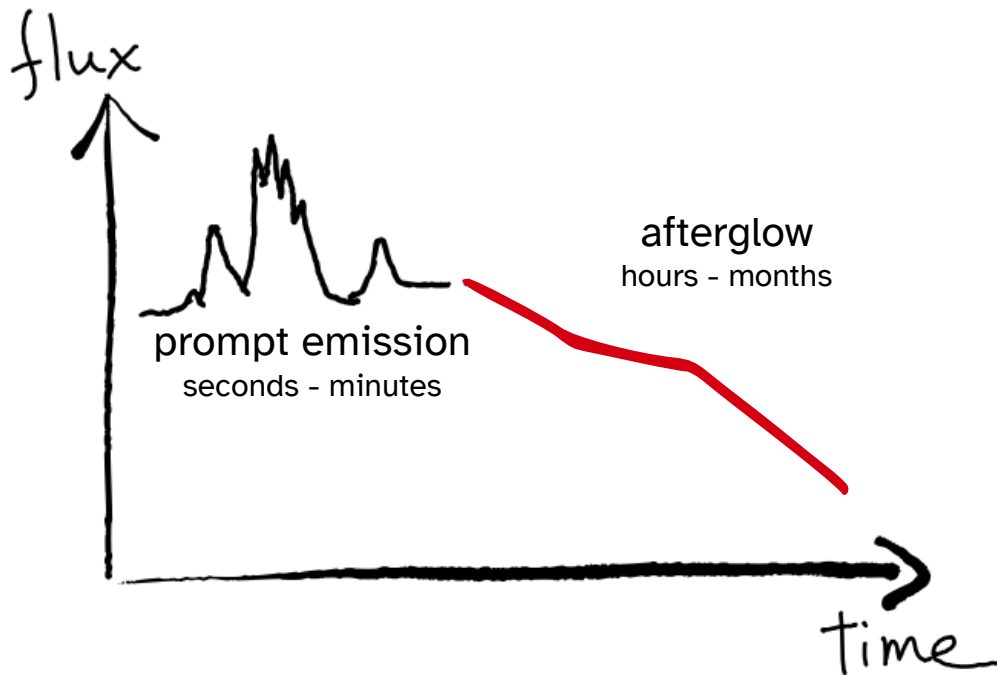
M. Ajello et al., ApJ 878 (2019)



P. Chandra & D. A. Frail, ApJ 746 (2012)

Gamma-ray bursts

What causes them?



Putting all the clues together:

GRBs are stellar-sized phenomena (not, e.g., galaxy-sized)

release $M_{\odot}c^2$ within minutes

emission occurring in regions smaller than the Earth

emission starts out highly variable but then evolves slowly and fades

stellar-mass compact objects are involved

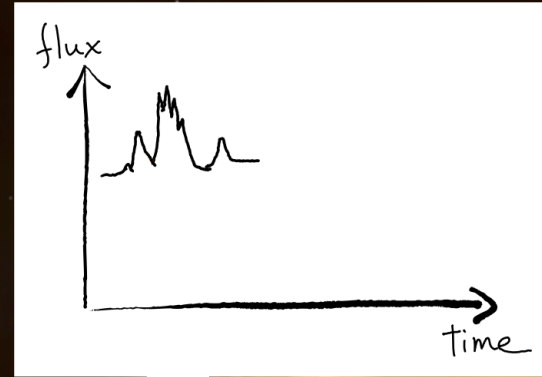
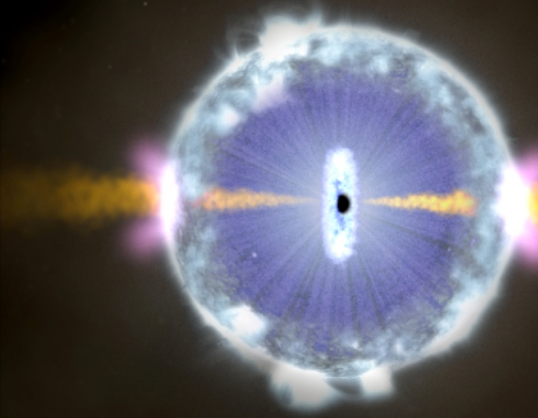

(stellar mass)
black
holes


neutron
stars

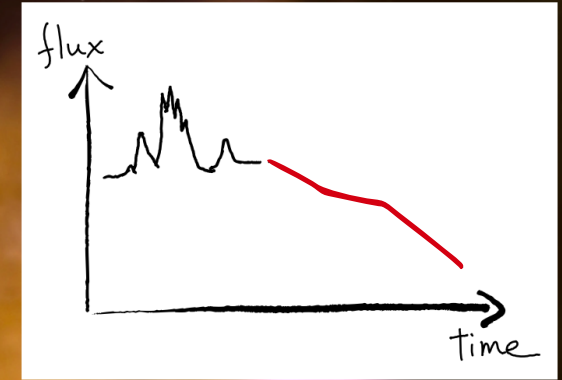
Gamma-ray bursts

What causes them?

[NASA's Goddard Space Flight Center]



internal shocks



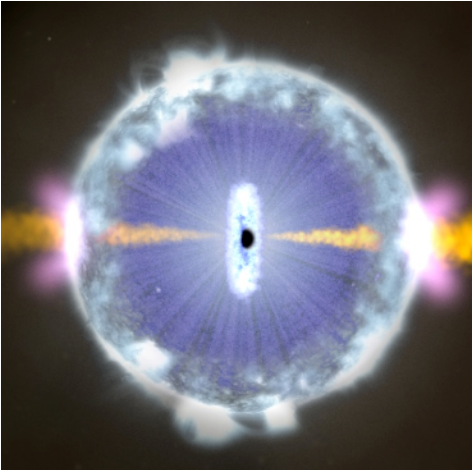
external shock

outflow moving with a bulk Lorentz factor $\Gamma_{\text{init}} \sim \mathcal{O}(100)$

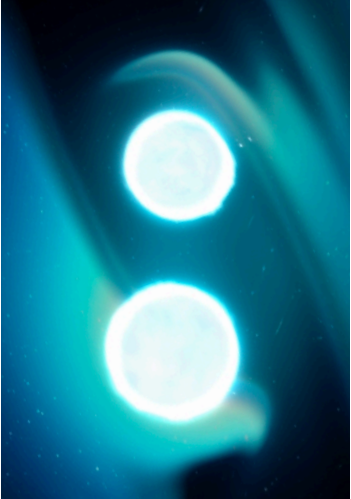
Gamma-ray bursts

What causes them?

[NASA's Goddard Space Flight Center]



NASA's Goddard Space Flight Center/CI Lab



two neutron stars merge
(probably)

or

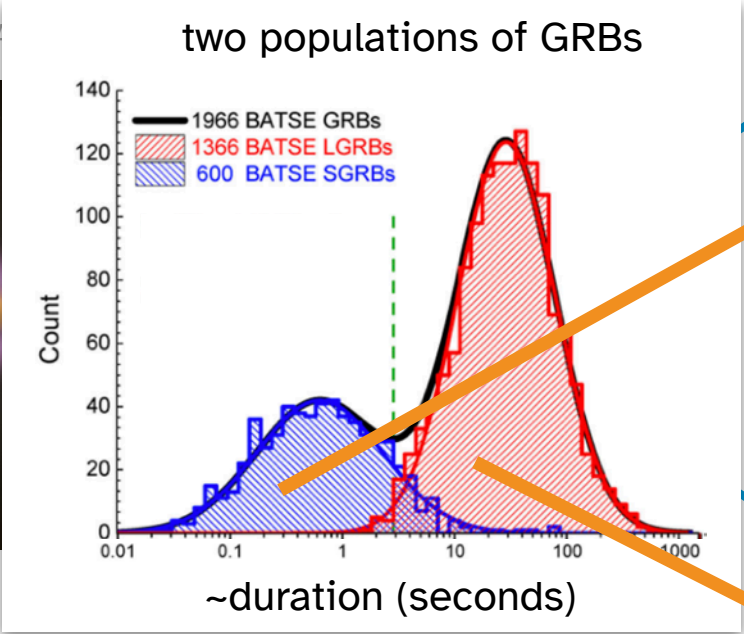
ESO/L Calçada



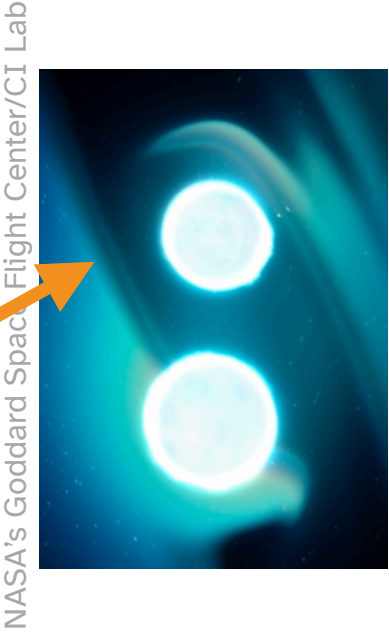
a massive star collapses

Gamma-ray bursts

What causes them?

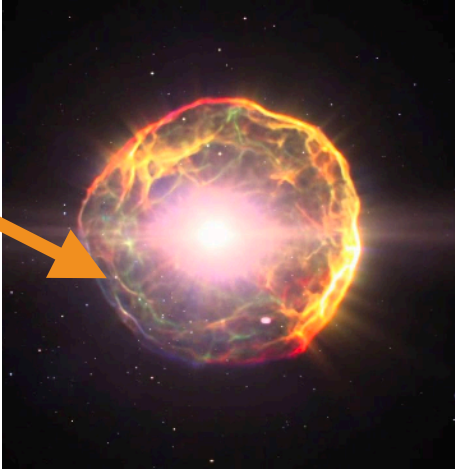


(mostly)



two neutron stars merge
(probably)

or

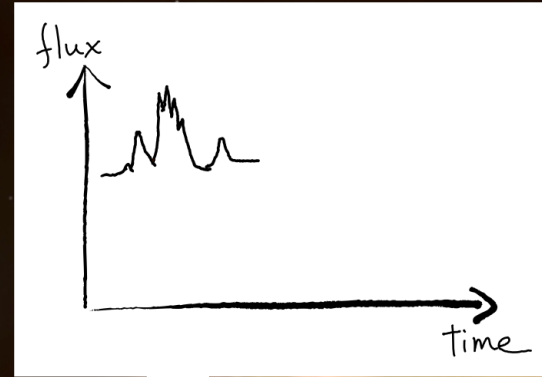
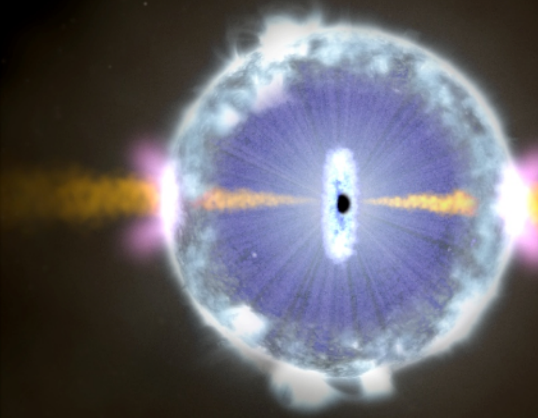


a massive star collapses

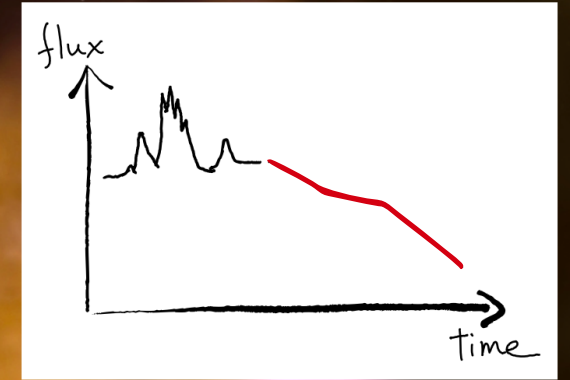
Gamma-ray bursts

What causes them?

[NASA's Goddard Space Flight Center]



internal shocks



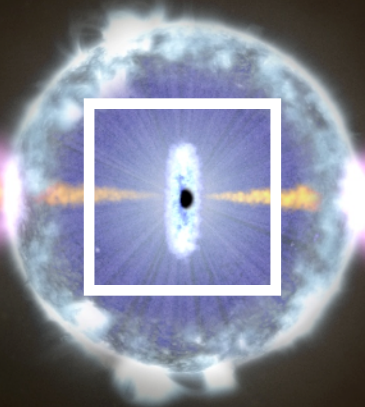
external shock

outflow moving with a bulk Lorentz factor $\Gamma_{\text{init}} \sim \mathcal{O}(100)$

Gamma-ray bursts

What causes them?

[NASA's Goddard Space Flight Center]



What is the central engine?



We know both black holes and neutron stars can produce jets from accreting material

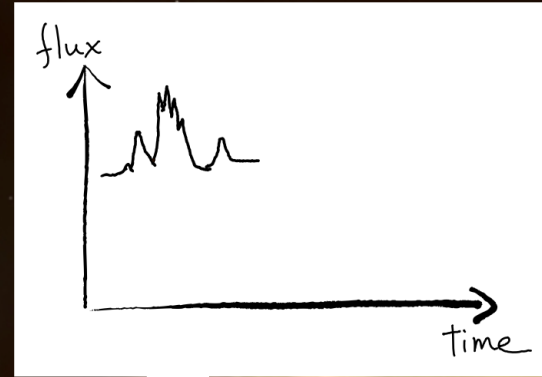
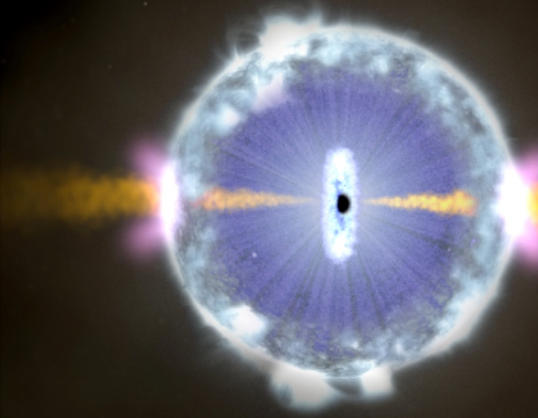
For GRBs in particular:

- Simulations can more easily launch jets with black holes (cannot fully produce for neutron stars yet); but:
- Neutron star central engine more naturally explains certain lightcurve features

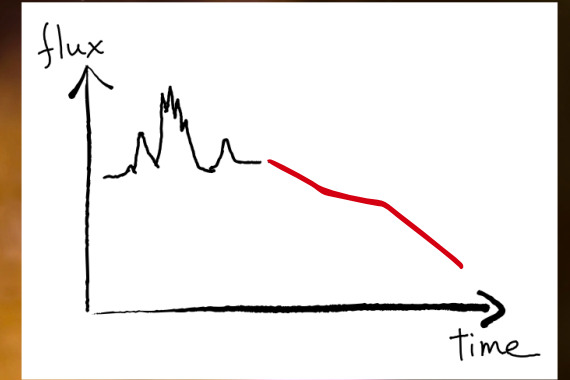
Gamma-ray bursts

What causes them?

[NASA's Goddard Space Flight Center]



internal shocks



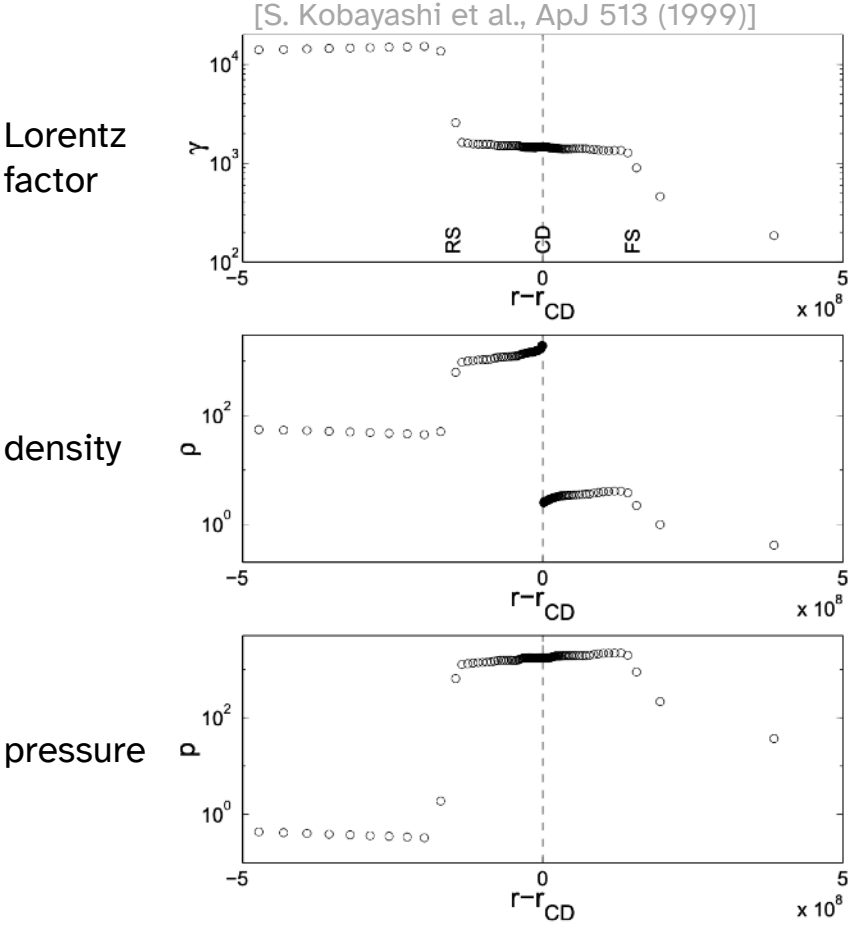
external shock

outflow moving with a bulk Lorentz factor $\Gamma_{\text{init}} \sim \mathcal{O}(100)$

Brief pause while a data analyst tries to explain shock physics

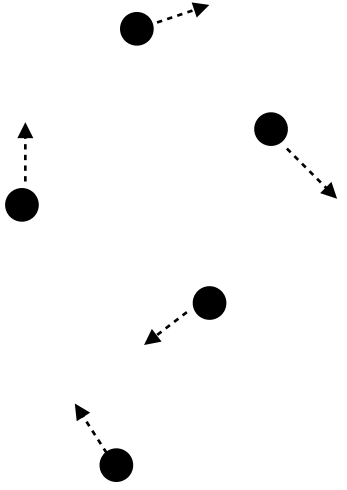


most relevant for high-energy astrophysical phenomena: relativistic **collisionless shocks**



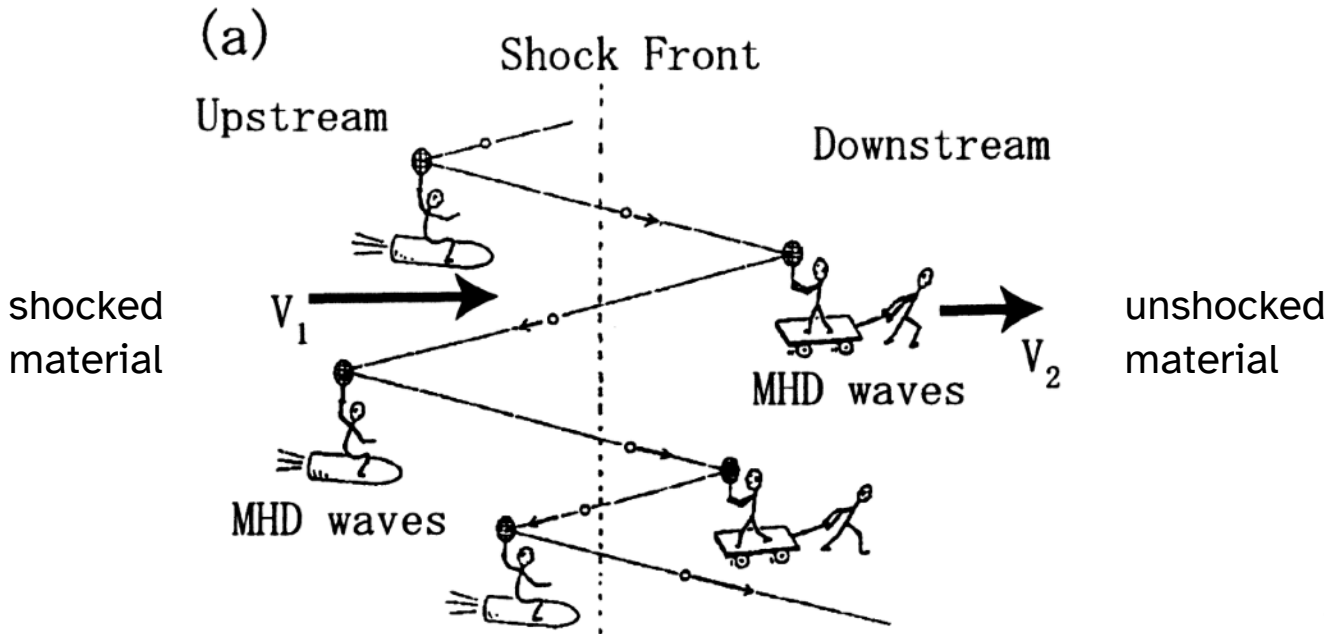
shock size is much smaller than particle's mean free path
=> electromagnetic interactions determine the behavior

shock ~ discontinuity in some physical parameters, transition in others



Brief pause while a data analyst tries to explain shock physics

most relevant for high-energy astrophysical phenomena: relativistic **collisionless shocks**
charged particles are accelerated at these shocks



e.g., first order Fermi acceleration:
particles gain energy with each
shock crossing

to actually learn about collisionless shocks:
[A. Marcowith et al., Rep Prog Phys 79 (2016)]

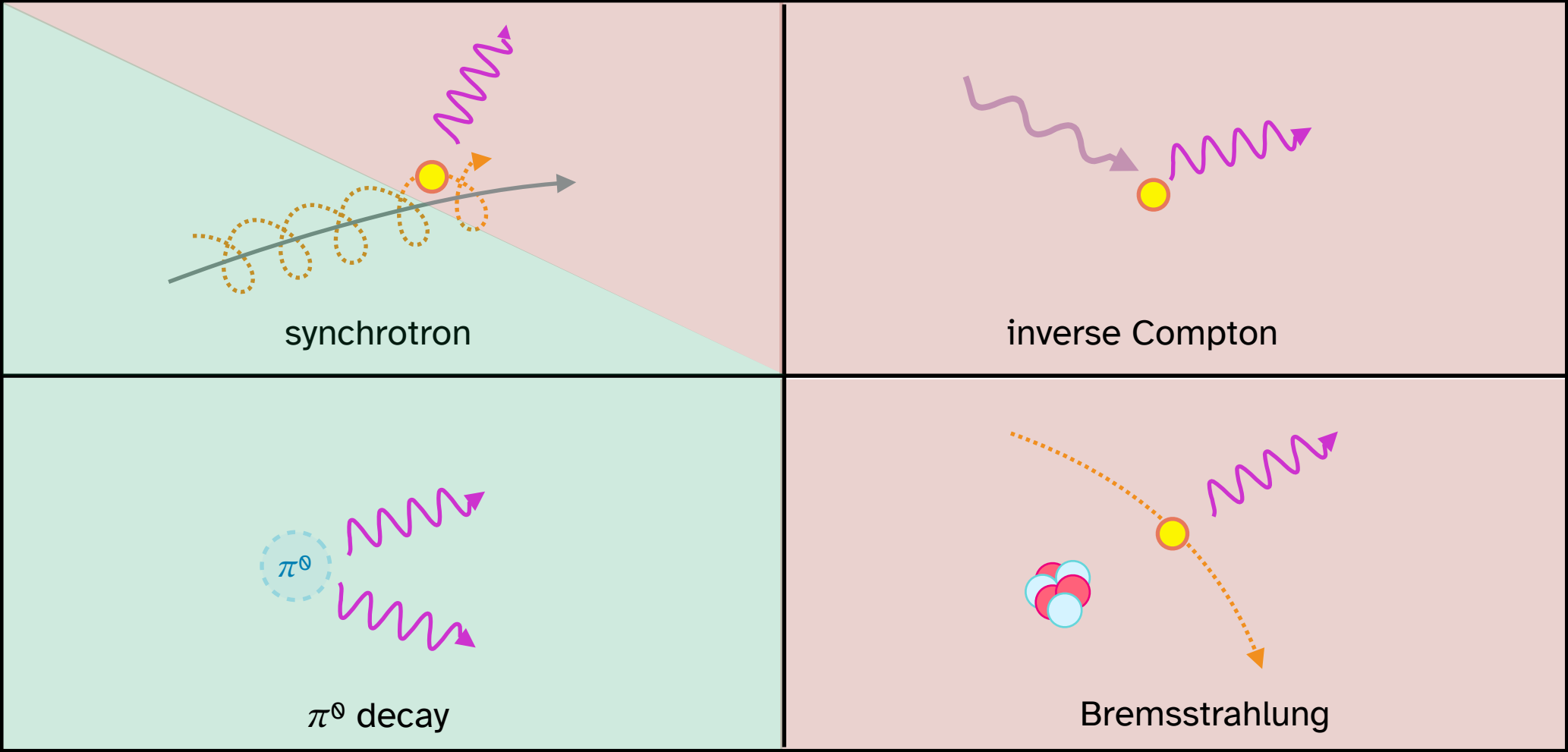
How do we get gamma rays?

Nonthermal emission

(coloring indicates what is relevant to these lectures)

Charged particles are **accelerated** to high energies before radiating photons

The charged particles can be **leptons** (e.g., electrons) or **hadrons** (e.g., protons)



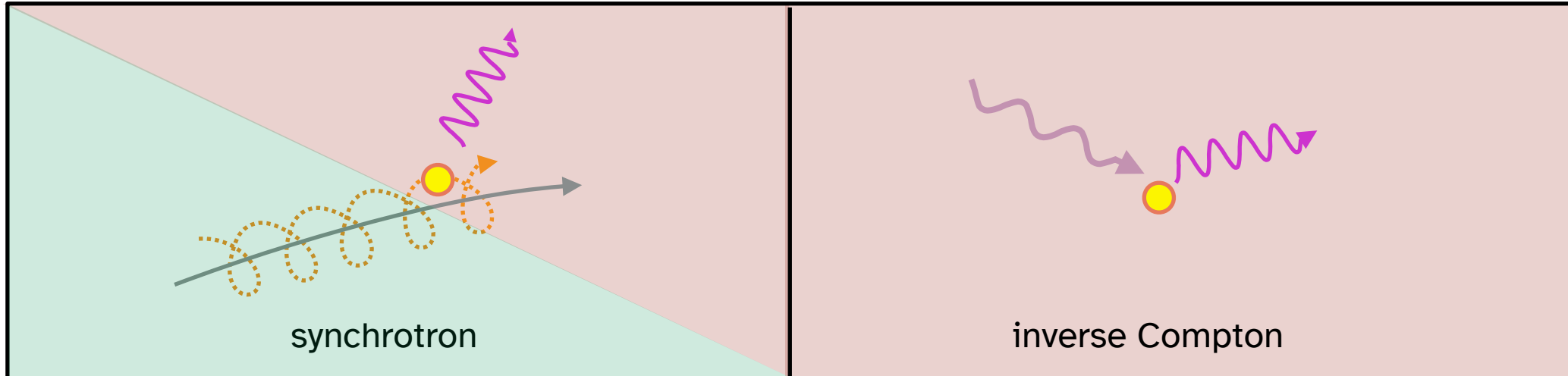
How do we get gamma rays?

Nonthermal emission

(coloring indicates what is relevant to these lectures)

Charged particles are **accelerated** to high energies before radiating photons

The charged particles can be **leptons** (e.g., electrons) or **hadrons** (e.g., protons)

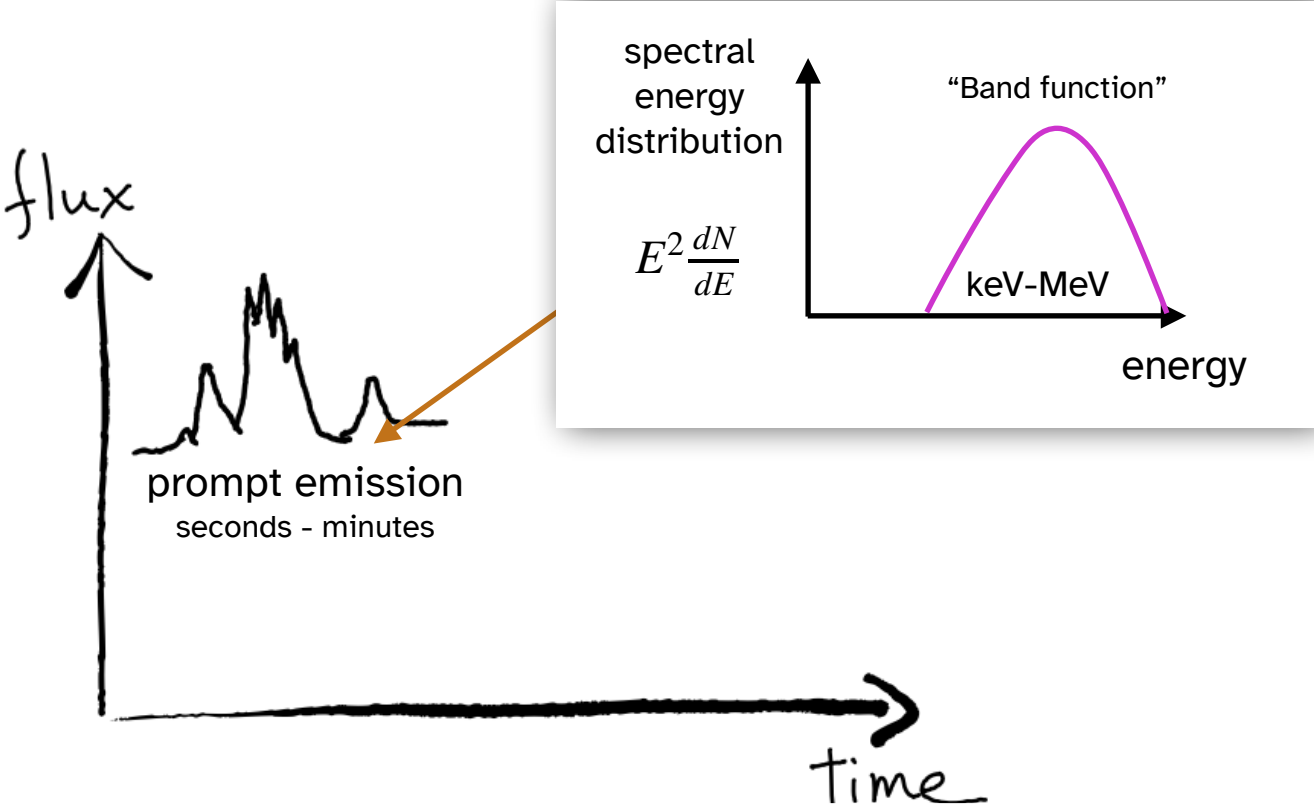


GRB jets have $\Gamma > 100$ => Must have low **baryon loading** (i.e., not too many heavy things absorbing energy)
=> conditions are most favorable for (leptonic) synchrotron and IC



GRB photon emission

Prompt emission



depending on who you ask

Prompt emission is probably lepton synchrotron, from particles accelerated ...

at internal shocks (matter dominated)

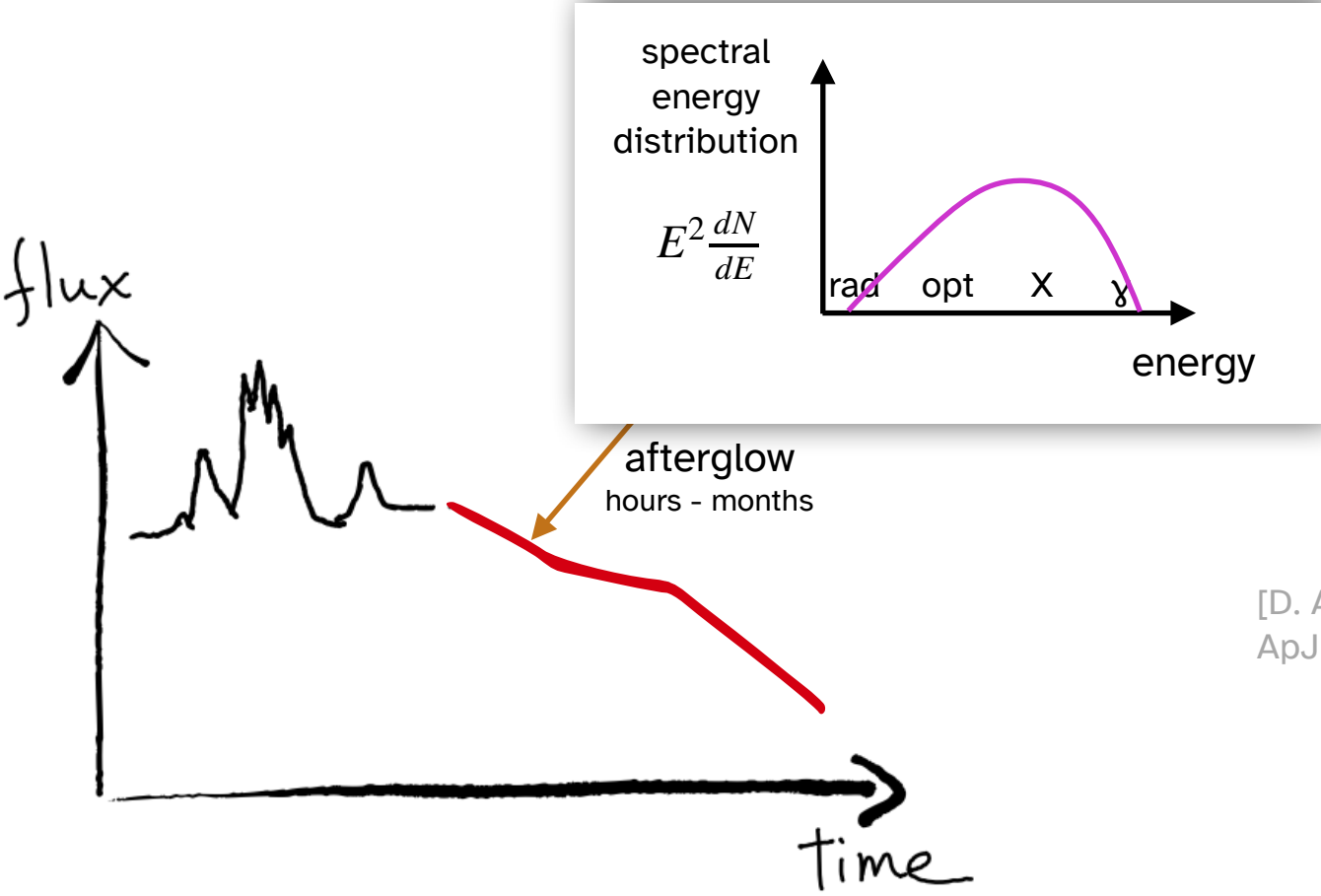
or

by magnetic fields (electromagnetic dominated)

Most likely a combination of the two

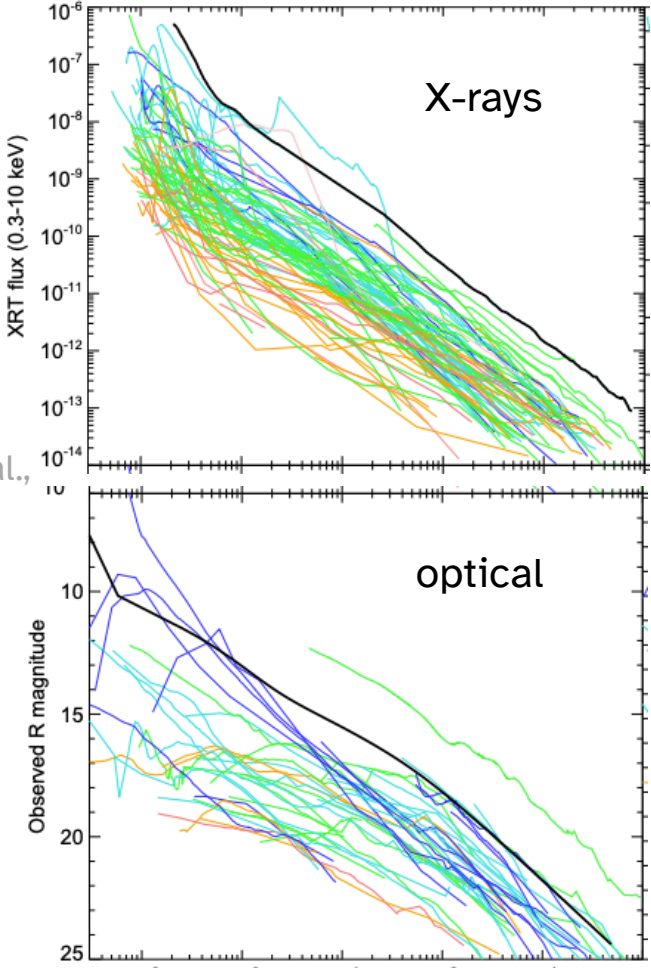
GRB photon emission

Afterglow emission



depending on who you ask

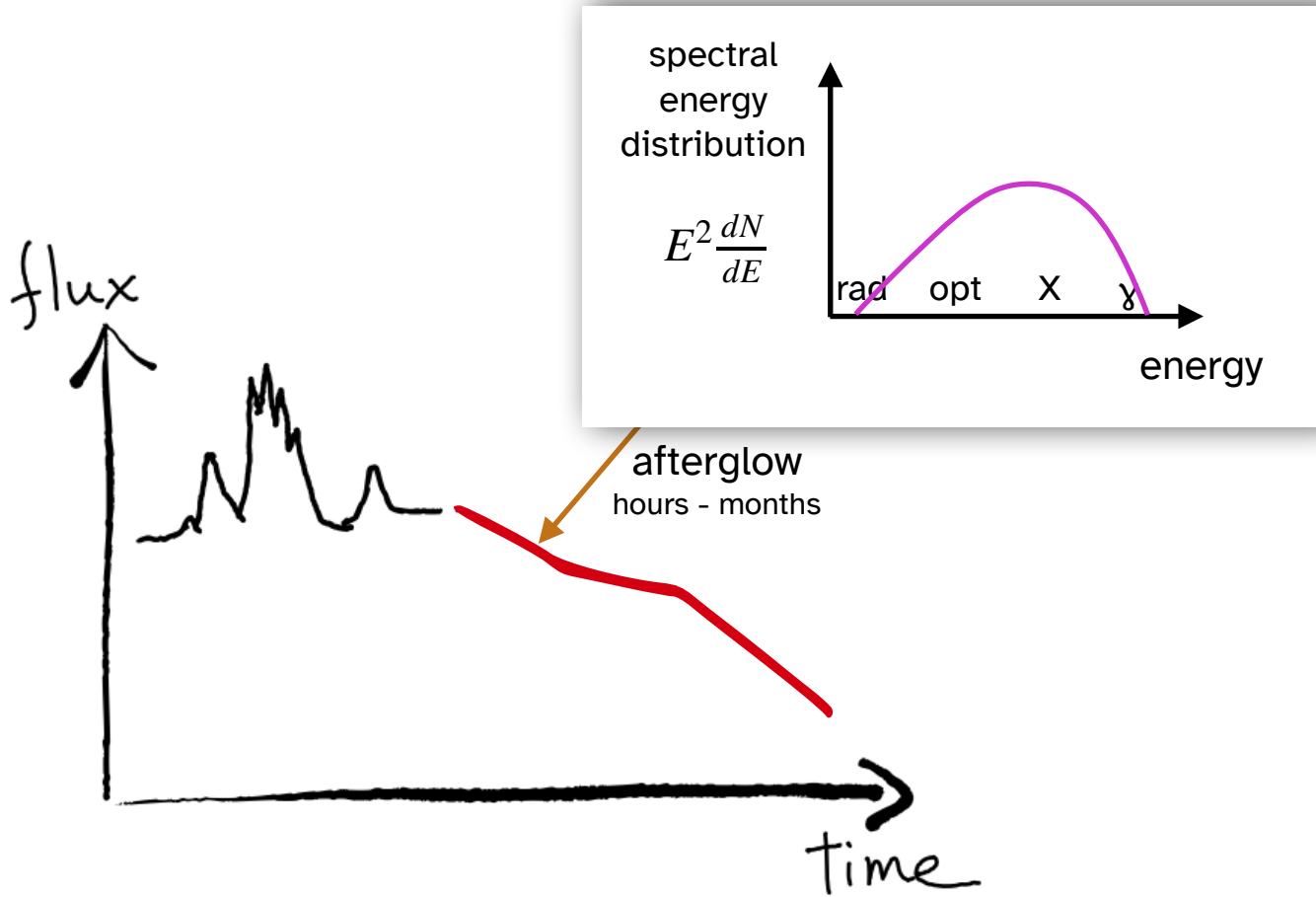
Afterglow emission is well established as leptonic synchrotron from external shocks



[D. A. Perley et al.,
ApJ 781 (2014)]

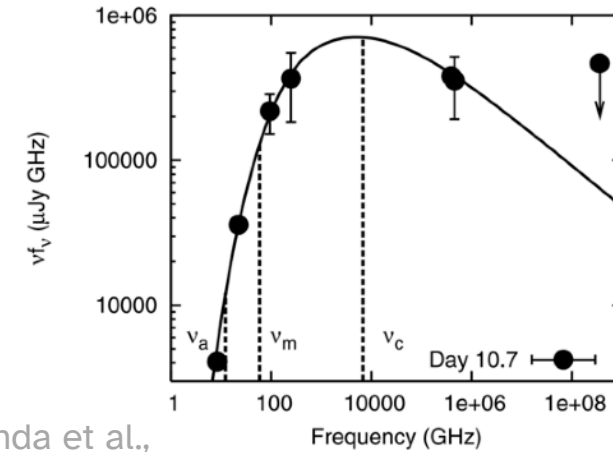
GRB photon emission

Afterglow emission

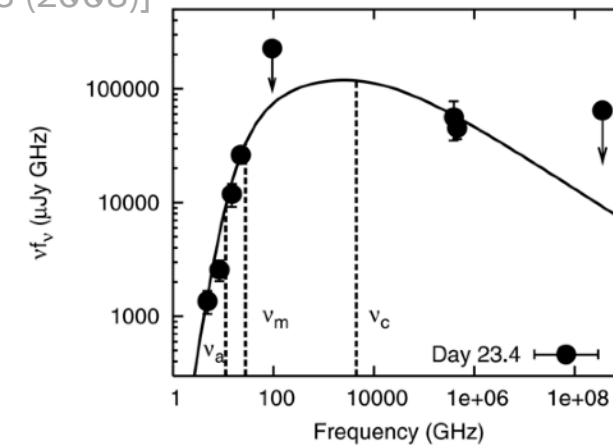


depending on who you ask

Afterglow emission is well established as leptonic synchrotron from external shocks

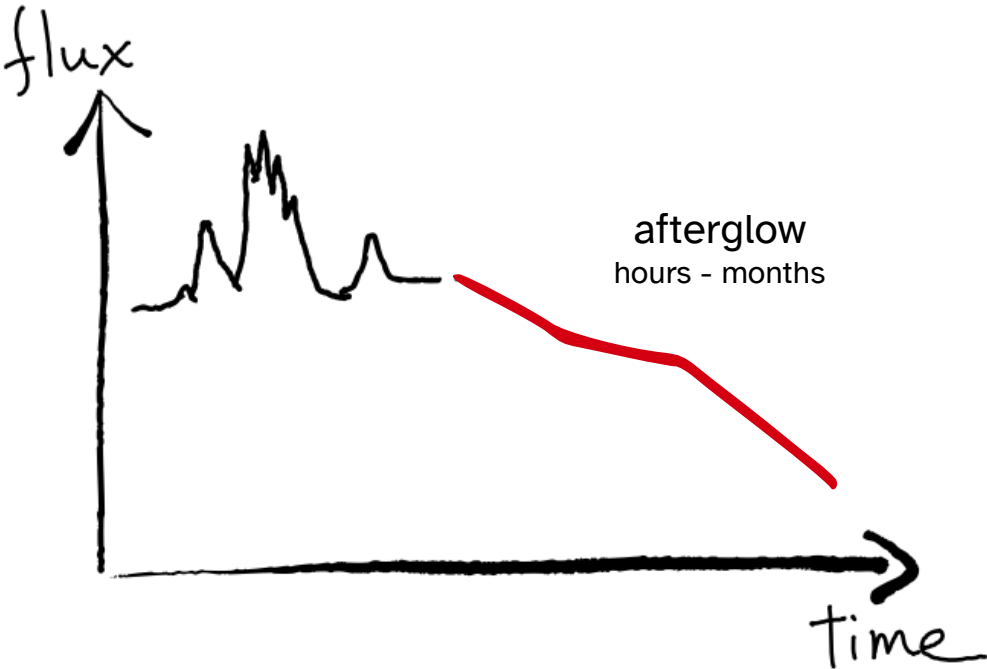


[P. Chanda et al.,
ApJ 683 (2008)]

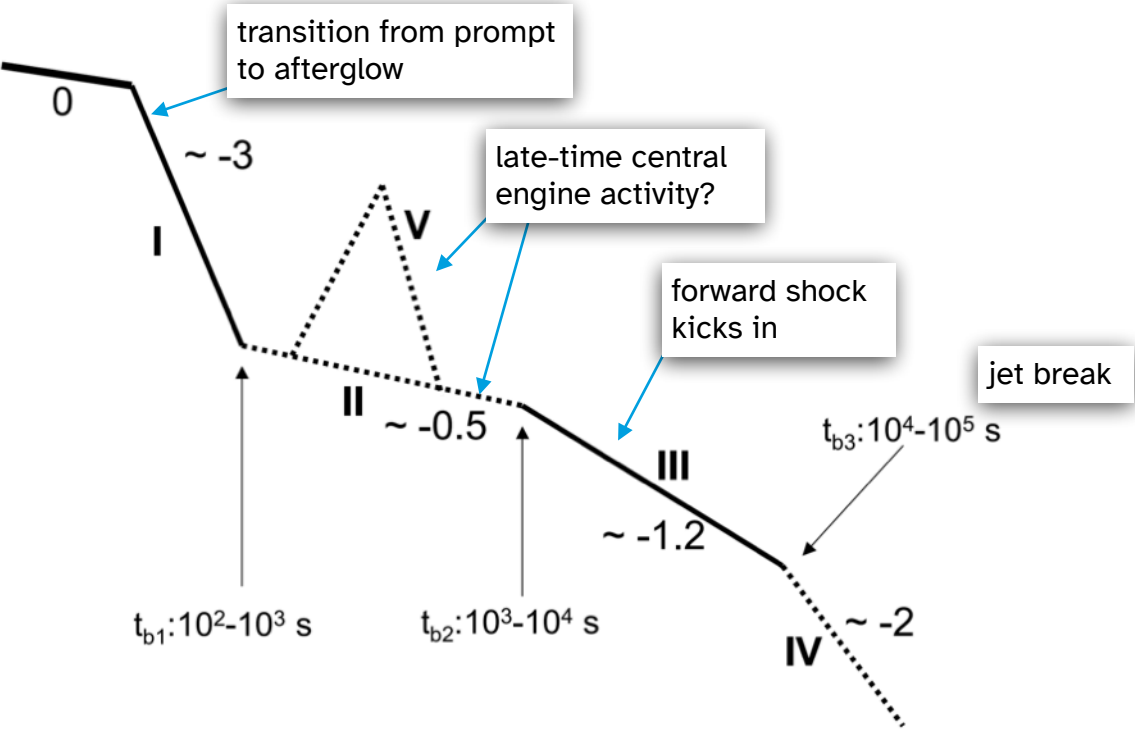


GRB photon emission

Afterglow emission



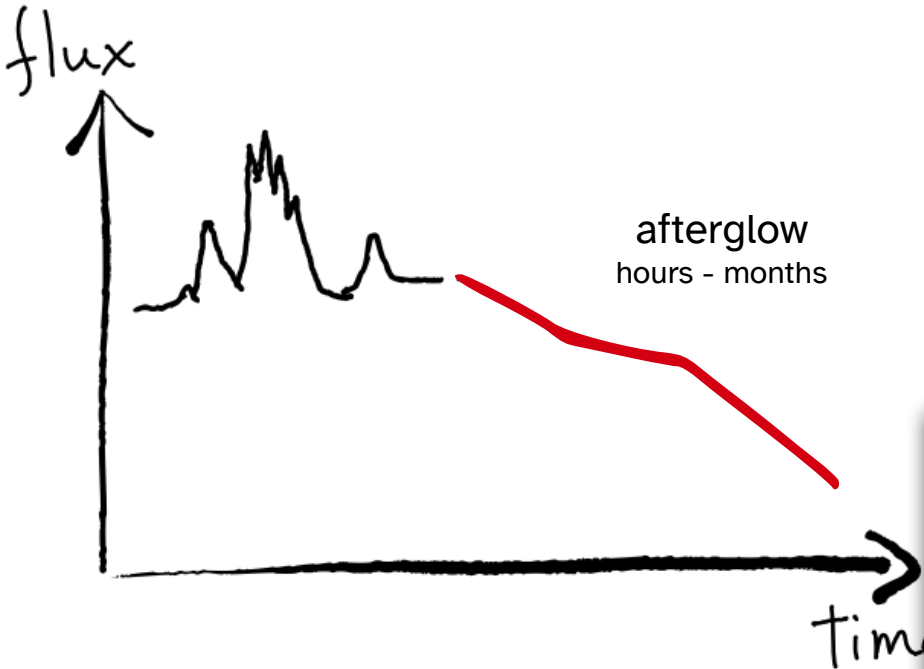
“canonical” X-ray afterglow lightcurve



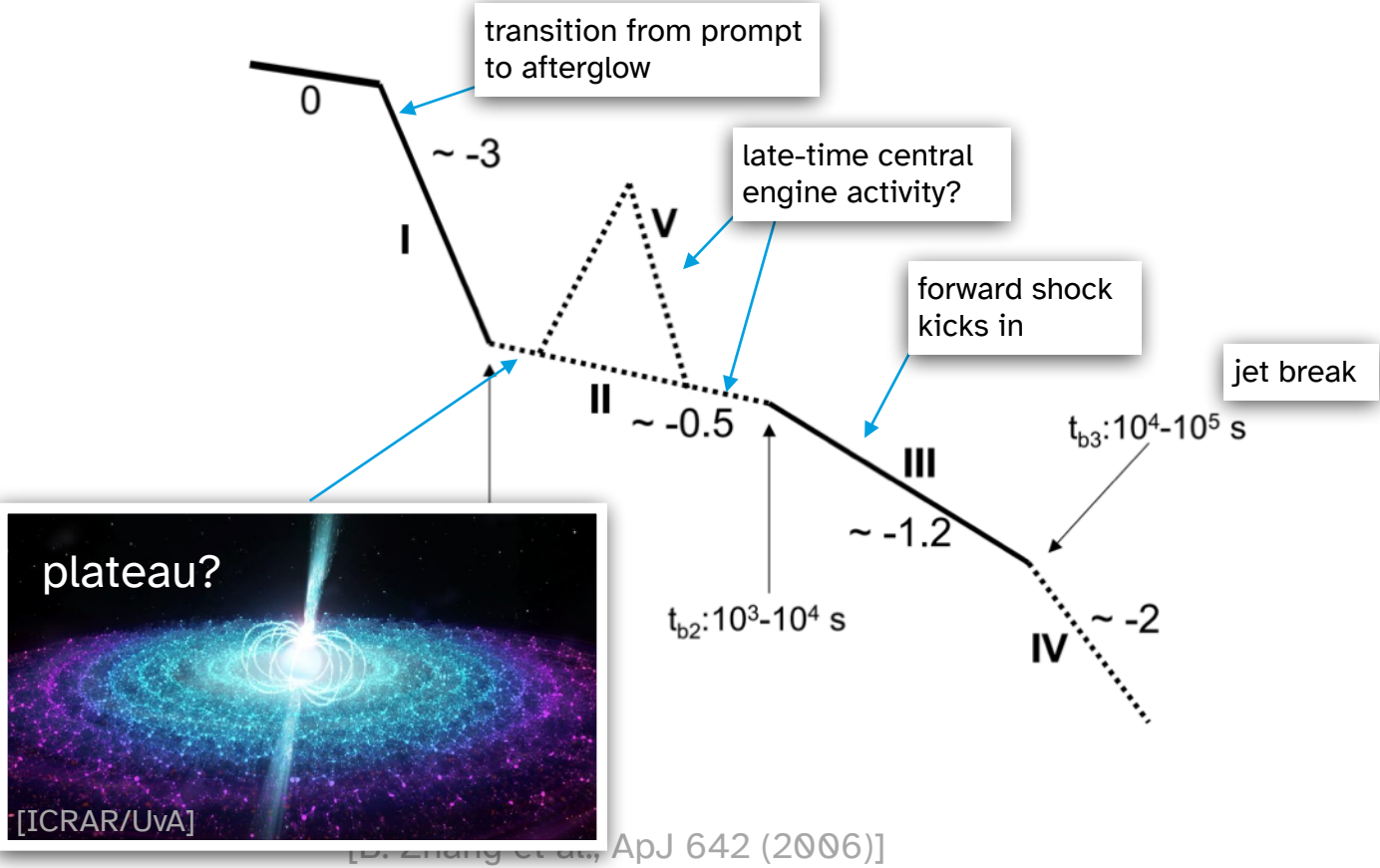
[B. Zhang et al., ApJ 642 (2006)]

GRB photon emission

Afterglow emission

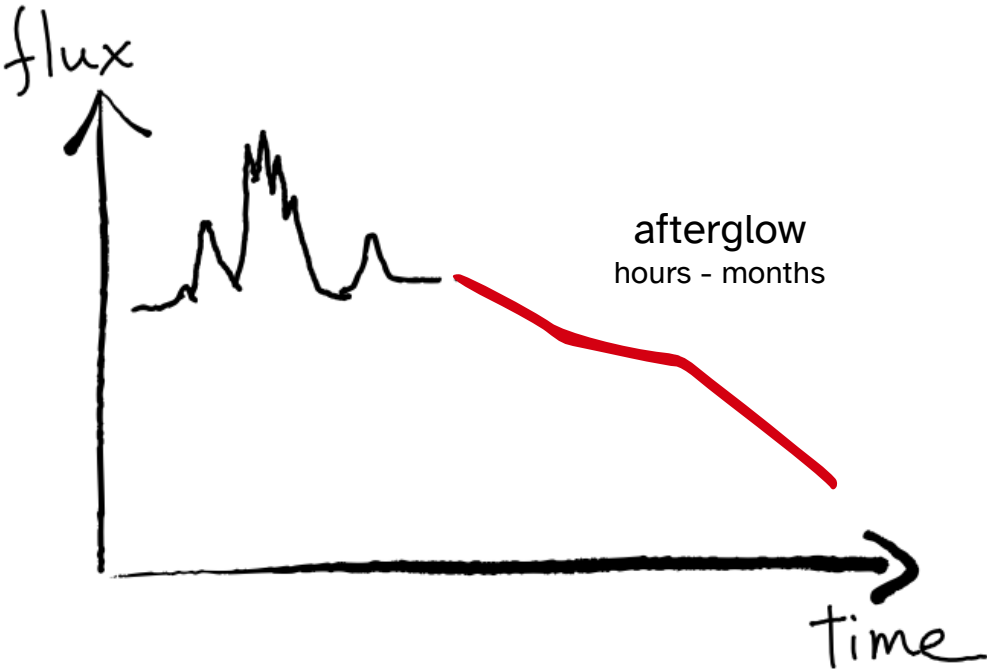


“canonical” X-ray afterglow lightcurve

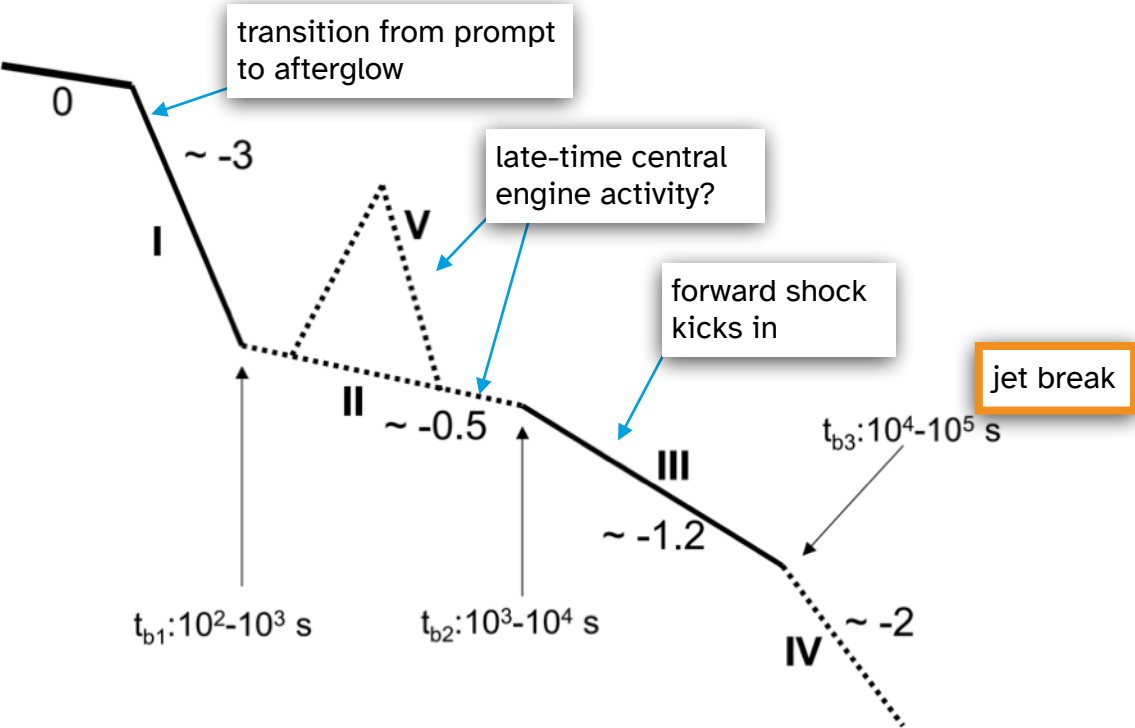


GRB photon emission

Afterglow emission



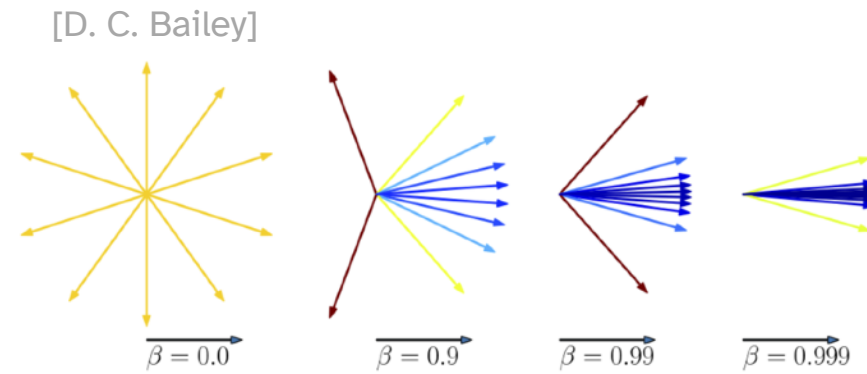
“canonical” X-ray afterglow lightcurve



[B. Zhang et al., ApJ 642 (2006)]

GRB jet break

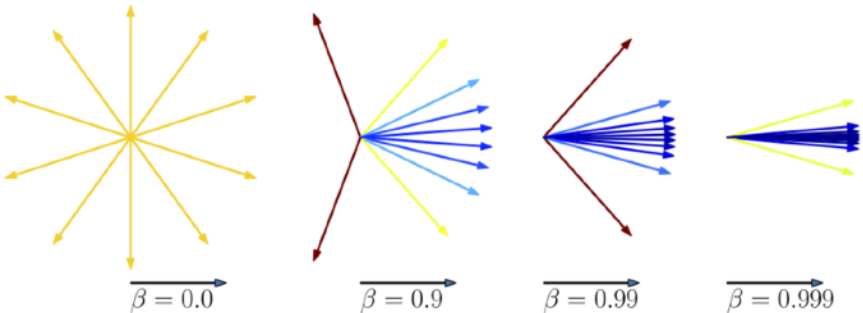
GRB emission is relativistically beamed



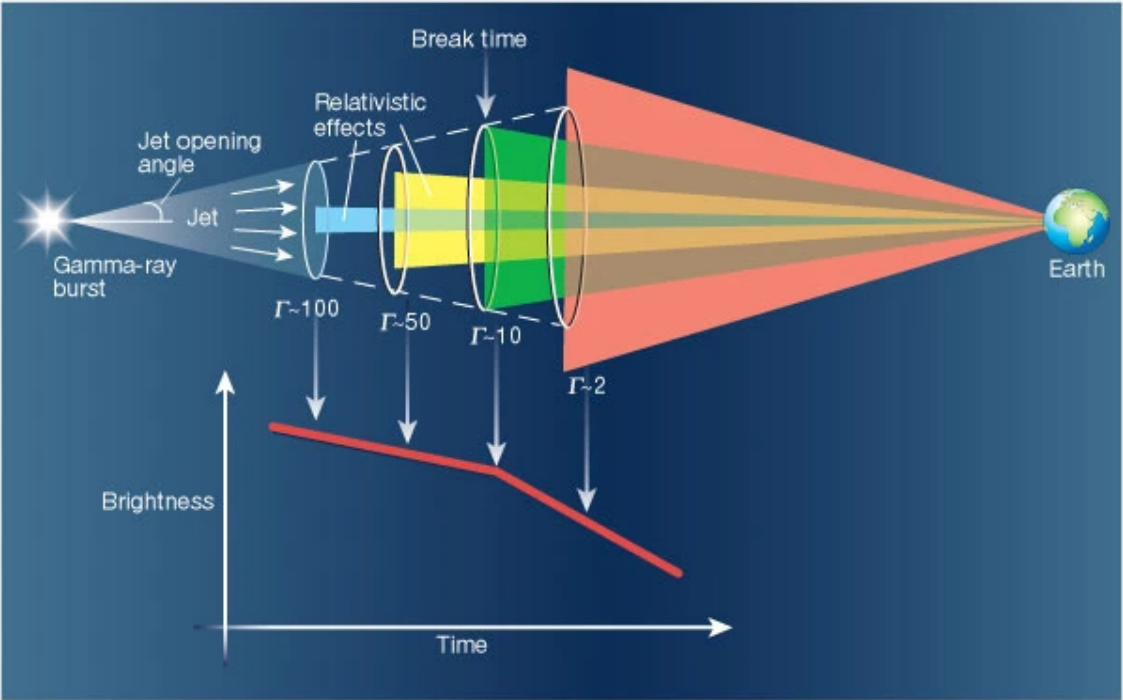
GRB jet break

GRB emission is relativistically beamed

[D. C. Bailey]

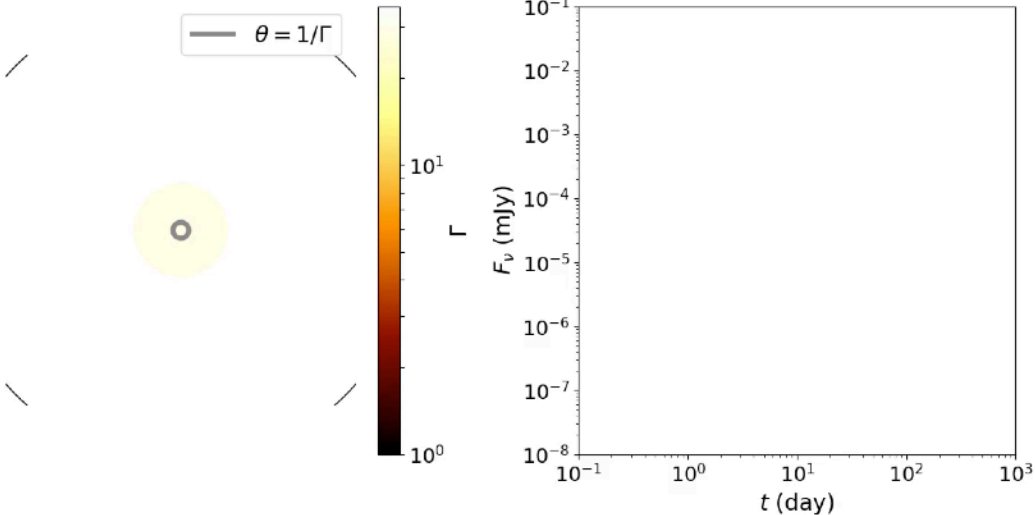


[S. Woosley, Nature 414 (2001)]



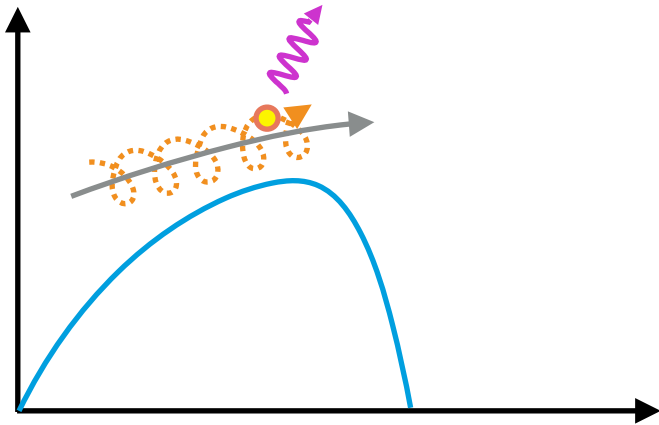
More of the emitting surface becomes visible at later times as the jet slows

G. Ryan, Perimeter Institute



GRB photon emission

Afterglow emission: one-zone synchrotron model

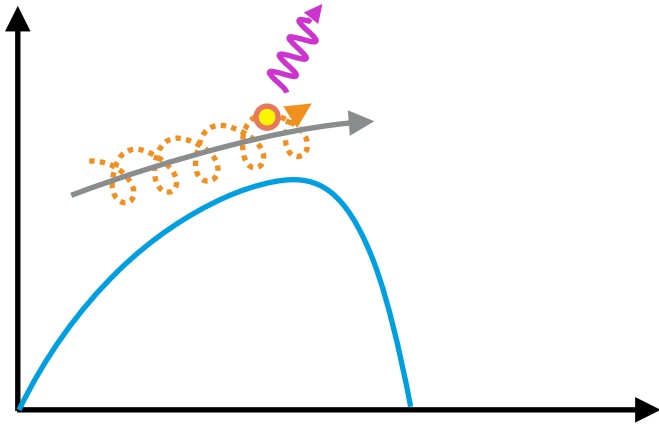


In general, gamma-ray bursts produce most of the afterglow via (electron) *synchrotron emission*

although there are exceptions, and it's usually not very clear what it is, and how the synchrotron spectrum should look depends on a lot of other factors, and there are other possibilities that could explain the emission, and sometimes electron synchrotron doesn't work very well at all ...

GRB photon emission

Afterglow emission: one-zone synchrotron model



In general, gamma-ray bursts produce most of the afterglow via (electron) *synchrotron emission*

GRB afterglow modeling almost always assumes a **one zone** scenario: The same magnetic field strength is responsible for both the **acceleration** and the **cooling**

If we balance the acceleration and cooling timescales, we can calculate a theoretical maximum synchrotron photon energy:

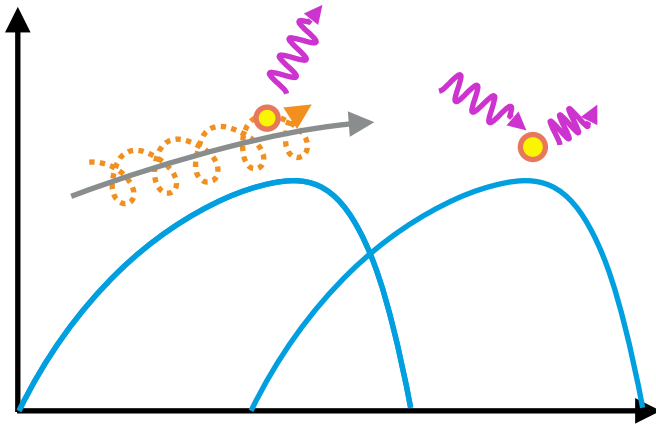
$$E_{\max} \sim \mathcal{O}(100) \text{ MeV}$$

(actual value depends on Γ)

learn more: [P. Kumar et al., MNRAS 427 (2012)]

GRB photon emission

Afterglow emission: one-zone synchrotron model



In general, gamma-ray bursts produce most of the afterglow via (electron) *synchrotron emission*

Inverse Compton is usually invoked for photons $\gtrsim \text{GeV}$

GRB afterglow modeling almost always assumes a **one zone** scenario: The same magnetic field strength is responsible for both the **acceleration** and the **cooling**

If we balance the acceleration and cooling timescales, we can calculate a theoretical maximum synchrotron photon energy:

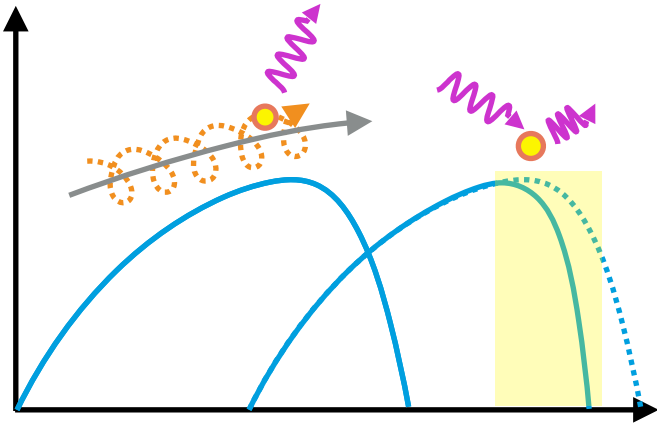
$$E_{\text{max}} \sim \mathcal{O}(100) \text{ MeV}$$

(actual value depends on Γ)

learn more: [P. Kumar et al., MNRAS 427 (2012)]

GRB photon emission

Afterglow emission: one-zone synchrotron model

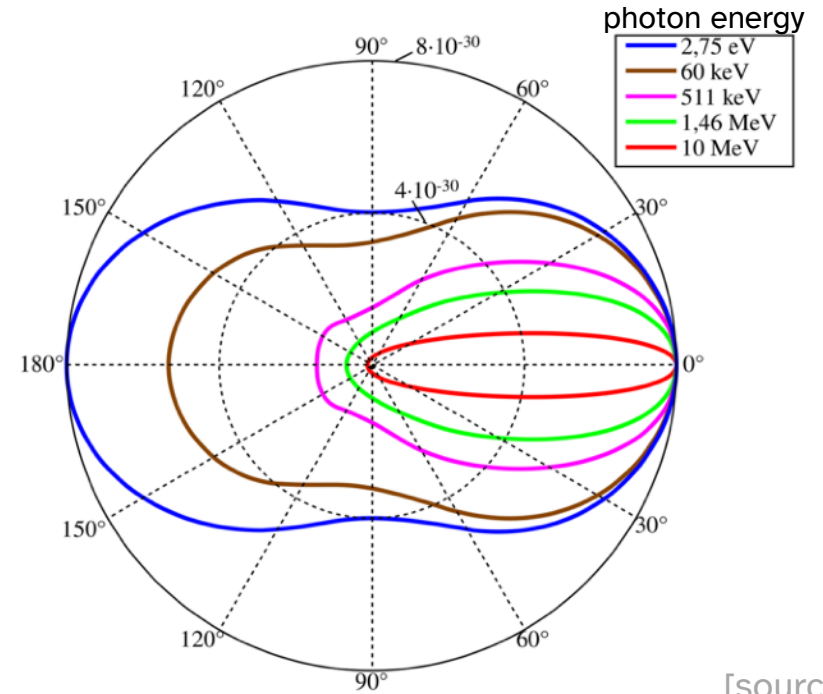


In general, gamma-ray bursts produce most of the afterglow via (electron) *synchrotron emission*

Inverse Compton is usually invoked for photons $\gtrsim \text{GeV}$

At TeV energies, we expect a very **steep** spectrum as the interaction cross section greatly decreases

interaction cross section for
(inverse) Compton scattering



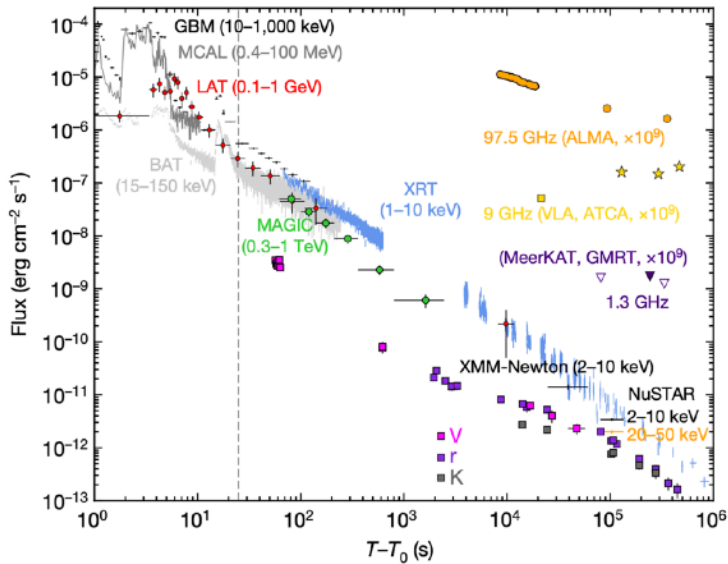
[source]

Do we see the inverse Compton component in VHE GRBs?

The three best test cases (imo)

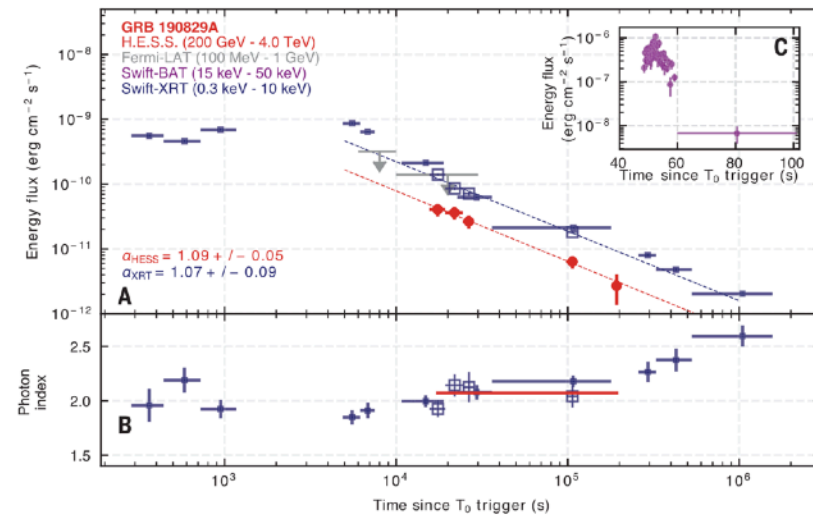
GRB 190114C

[MAGIC, Nature 575 (2019)]



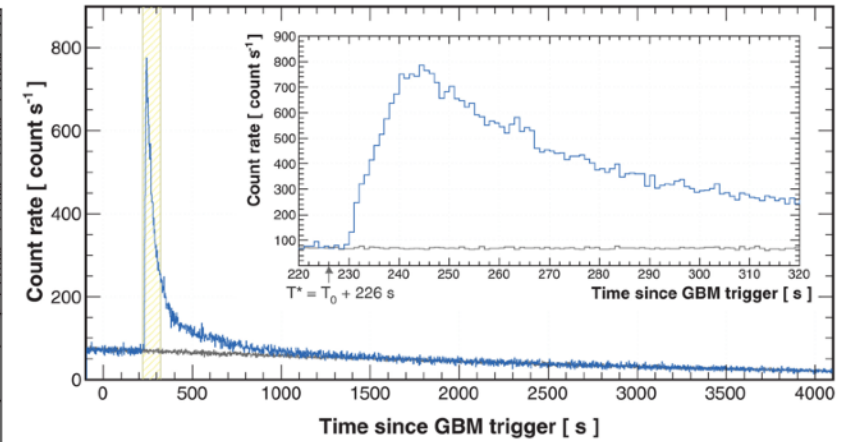
GRB 190829A

[H.E.S.S. et al., Science 372 (2021)]



GRB 221009A

[LHAASO, Science 380 (2023)]

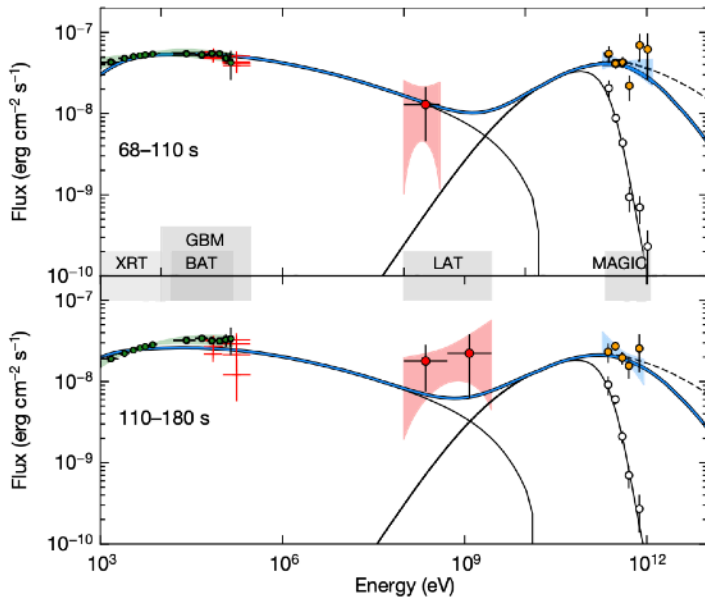


Do we see the inverse Compton component in VHE GRBs?

The three best test cases (imo)

GRB 190114C

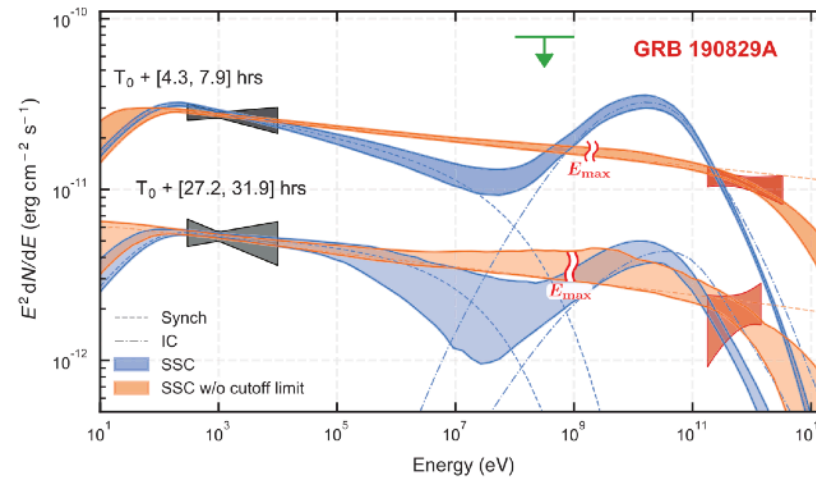
[MAGIC, Nature 575 (2019)]



“yes”

GRB 190829A

[H.E.S.S. et al., Science 372 (2021)]



“no”

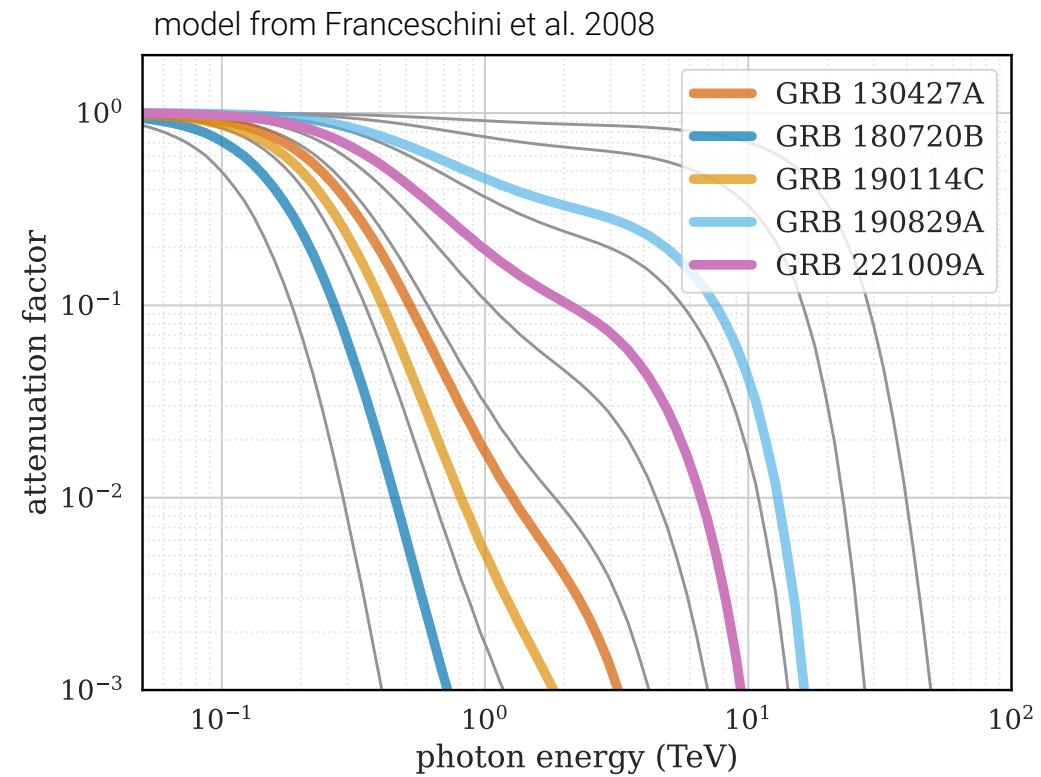
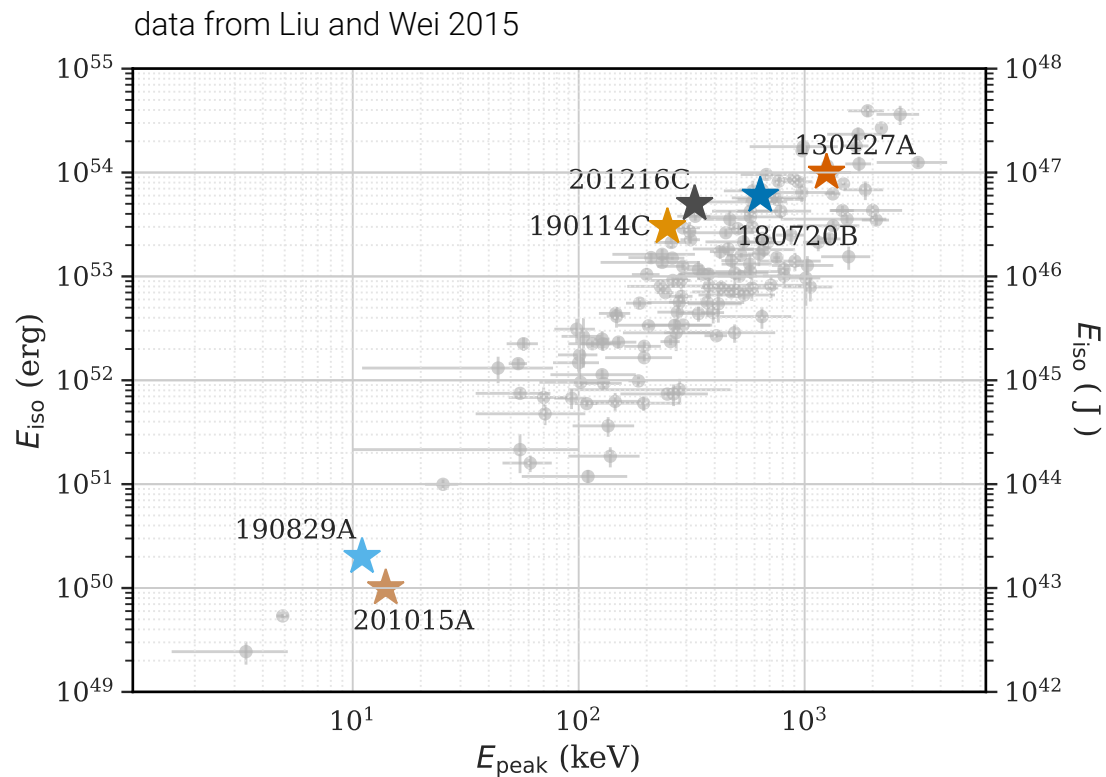
GRB 221009A

[LHAASO, Science 380 (2023)]

up next

Comparing the VHE GRBs as a population

$n < 10$



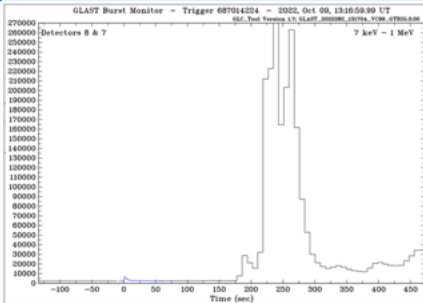
now let's talk about GRB 221009A

time-domain astronomy in realtime

up next: a set of slides from when this GRB went off right at the start of (or before?) the 2022 Fermi Symposium

ok fine let's briefly talk about GRB 221009A now

So what happened? — NOTE: Not an exhaustive list!!! Sorry if I missed your telescope!!!! pls forgive me :(



13:16:59 UTC, GBM triggers (GCN 32636)

“the brightest among the GBM detected GRBs”

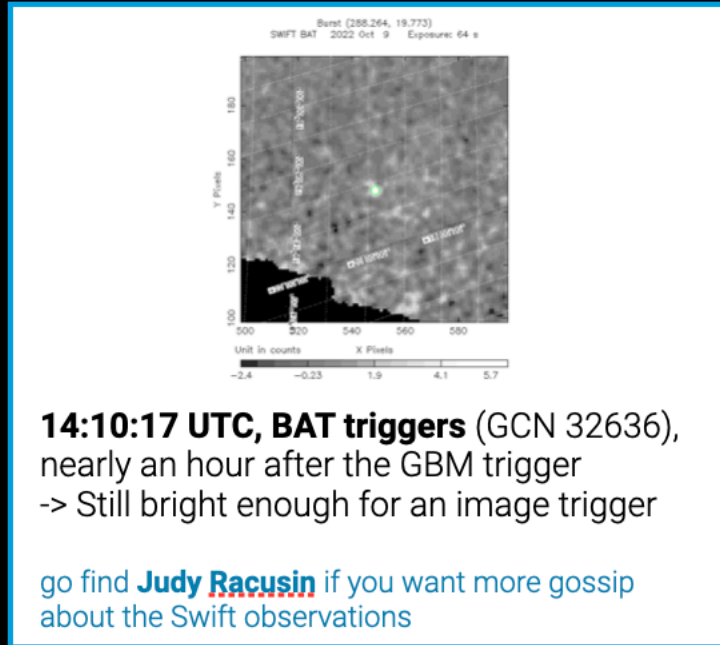
go find **Eric Burns** if you want more gossip about the GBM detection

At this time, the source is not visible to BAT



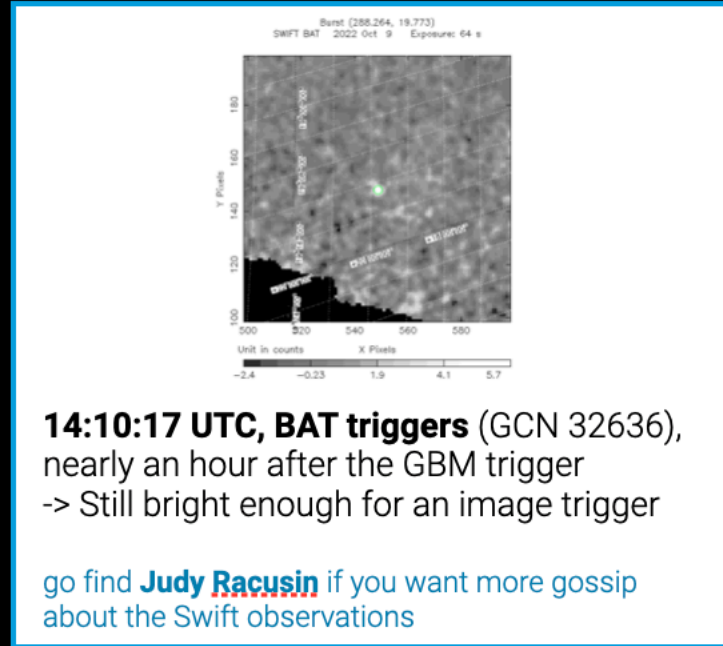
ok fine let's briefly talk about GRB 221009A now

So what happened? — NOTE: Not an exhaustive list!!! Sorry if I missed your telescope!!!! pls forgive me :(

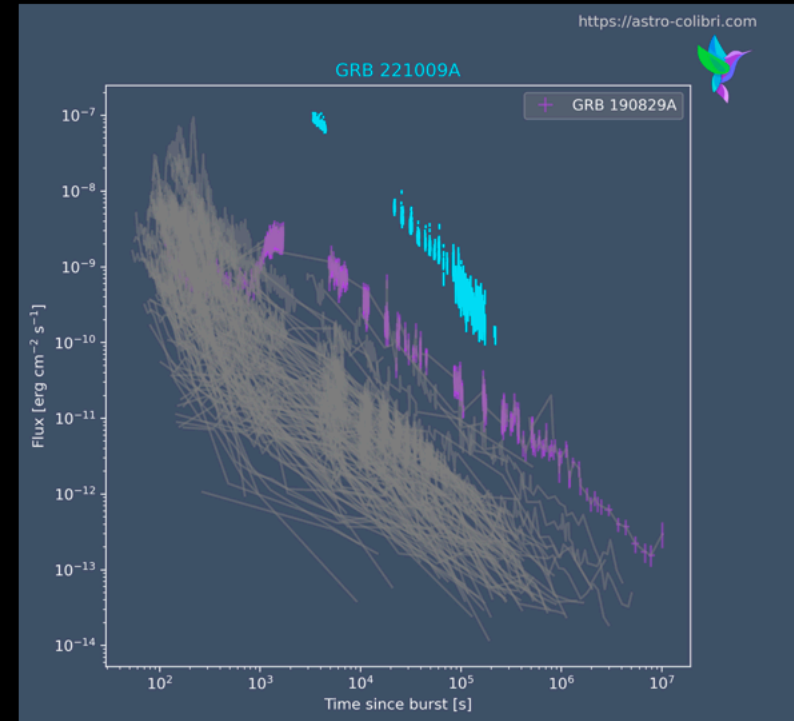


ok fine let's briefly talk about GRB 221009A now

So what happened? — NOTE: Not an exhaustive list!!! Sorry if I missed your telescope!!!! pls forgive me :(



brightest XRT afterglow by far



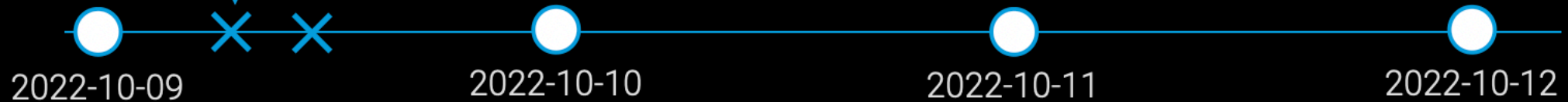
ok fine let's briefly talk about GRB 221009A now

So what happened? — NOTE: Not an exhaustive list!!! Sorry if I missed your telescope!!!! pls forgive me :(

LAT detected the prompt emission (GCNs 32637, 32658)

"bright structured emission episode ... temporally coincident with the GBM main emission episode"
"extending for about 25ks post GBM trigger"
"The highest-energy photon is 99.3 GeV ... 240 seconds after the GBM trigger."

go find [Nicola Omodei](#) if you want more gossip about the LAT detection



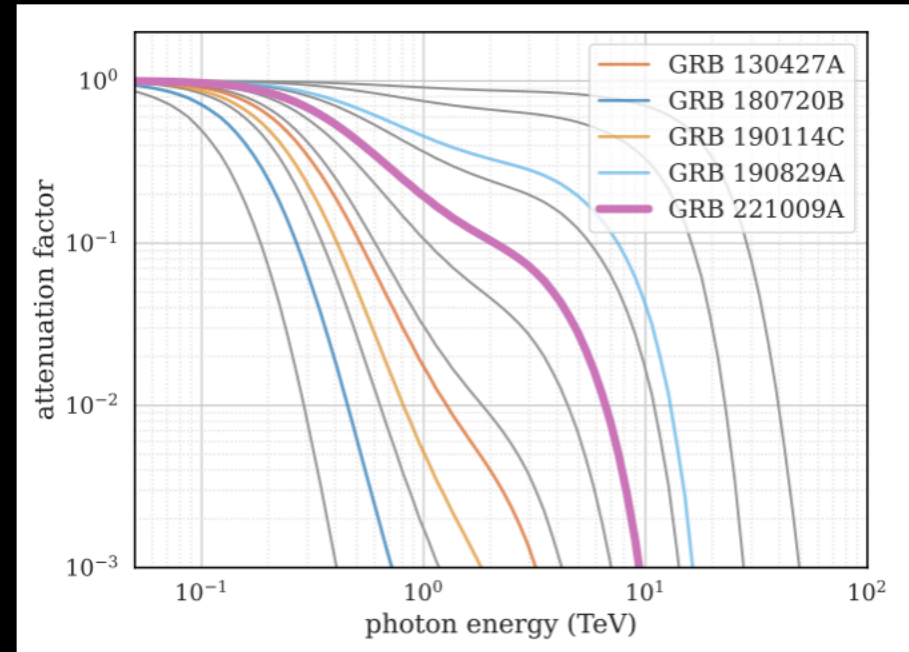
ok fine let's briefly talk about GRB 221009A now

So what happened? — NOTE: Not an exhaustive list!!! Sorry if I missed your telescope!!!! pls forgive me :(

X-shooter/VLT: $z = 0.151$
(GCN 32648)

Eiso $\sim 2e54$ erg based on GBM fluence
but: GBM has strong systematic issues
because the burst was TOO BRIGHT

go find **Eric Burns** if you want more gossip about
the GBM systematic issues



2022-10-09



2022-10-10



2022-10-11

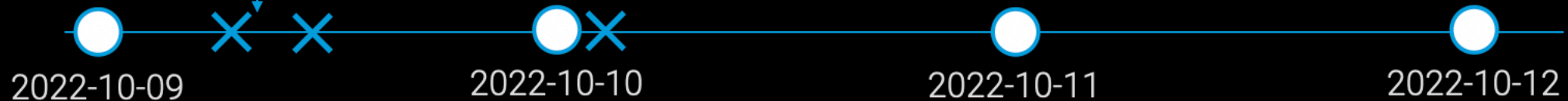
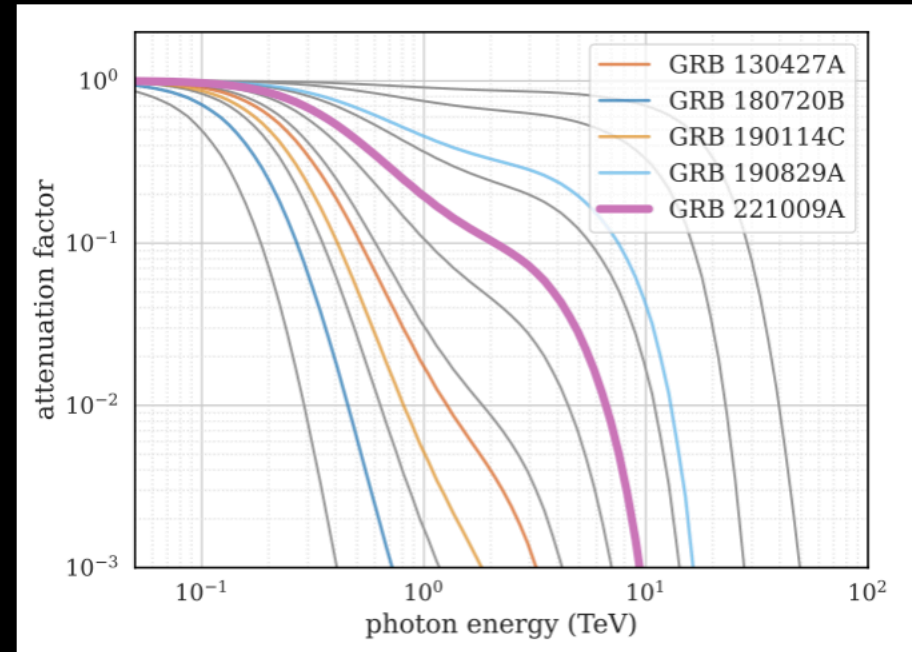
2022-10-12

ok fine let's briefly talk about GRB 221009A now

So what happened? — NOTE: Not an exhaustive list!!! Sorry if I missed your telescope!!!! pls forgive me :(

LHAASO (GCN 32677)

“more than 5000 VHE photons up to around 18 TeV” !!!!
(previous record: 4 TeV)
“within 2000 seconds after T0”



ok fine let's briefly talk about GRB 221009A now

Why have IACTs been so quiet???



full moon :(
bad for IACTs :(:(
we cant observe :(:(:(



ok fine let's briefly talk about GRB 221009A now

Why have IACTs been so quiet???



LHAASO	IACTs
	
18 TeV 100 sigma 5000 photons	the moooooon is too briiiiiight
<small>imgflip.com</small>	S. J. Zhu & D. Green



2022-10-09

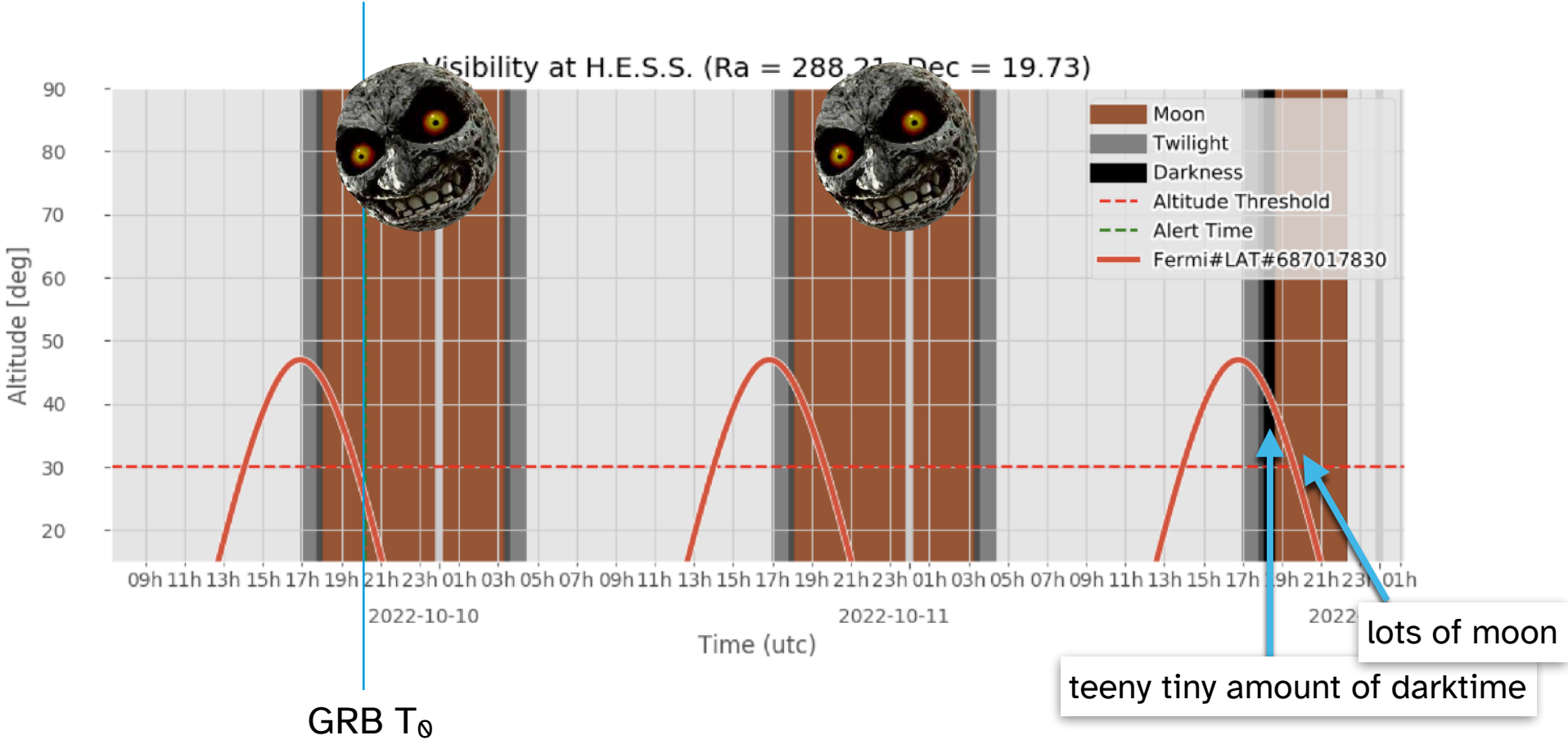
2-10-11

2022-10-12

GRB 221009A

IACTs tried

the IACTs observed as soon as we all could (even during extremely bright moonlight ...)



GRB 221009A

IACTs tried

the IACTs observed as soon as we all could (even during extremely bright moonlight ...)

conversations on 10 October



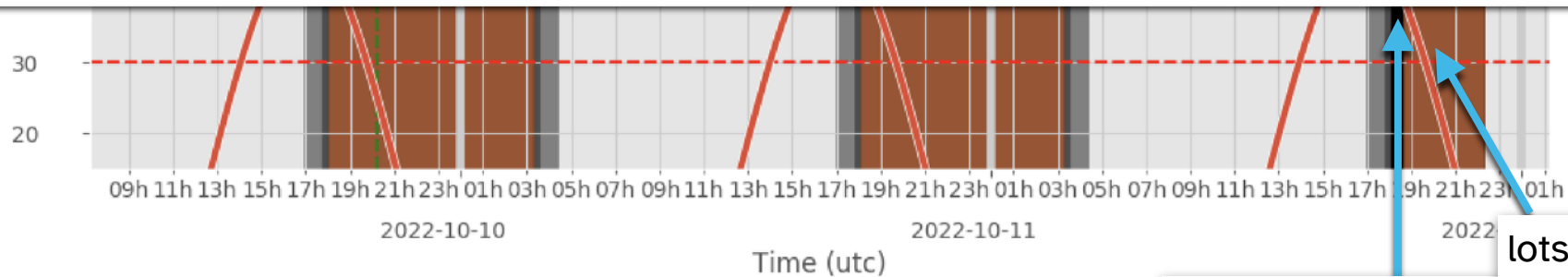
Fabian Schuessler 10:47 AM

Feedback from the operations channel: observations will start tomorrow. I think we should try to get as much observations as possible. At least one run with standard settings and then pushing into moonlight until the trigger rates become impossible...



Stefan Ohm 10:59 AM

If I were still OPS lead, I'd suggest to try to go beyond the end of darktime, closely monitor the rates and stop as soon as we hit the predetermined limit of 10 kHz with the HESS-IU cameras. Before starting observations, I'd reach out to the hess-op +EC list and inform them about what you propose to do. My guess is that we'll be able to gather a few more minutes, maybe complete a 2nd run, and then pretty quickly hit the wall. If we do it this way, I'd start the second run already as moonlight observation run. my two cents



so we tried it

lots of moon

teeny tiny amount of darktime

GRB 221009A

IACTs tried

the IACTs observed as soon as we all could (even during extremely bright moonlight ...)

conversations on 10 October



Fabian Schuessler 10:47 AM

Feedback from the operations channel: observations will start tomorrow. I think we should try to get as much observations as possible. At least one run with standard settings and then pushing into moonlight until the trigger rates become impossible...



Stefan Ohm 10:59 AM

If I were still OPS lead, I'd suggest to try to go beyond the end of darktime, closely monitor the rates and stop as soon as we hit the predetermined limit of 10 kHz with the HESS-IU cameras. Before starting observations, I'd reach out to the hess-op +EC list and inform them about what you propose to do. My guess is that we'll be able to gather a few more minutes, maybe complete a 2nd run, and then pretty quickly hit the wall. If we do it this way, I'd start the second run already as moonlight observation run. my two cents

The screenshot shows a video conference interface with a yellow background. At the top center, a large red digital timer displays "00:08:08". To the right of the timer, a blue arrow points to the text "countdown until start of observations". Below the timer, there is a text box containing the following information: "Observation date: 2022-10-11", "Darkness Start: 18:04:17 UTC / Duration: 00:31:27", and "No Moonlight tonight". At the bottom of the interface, there are five video thumbnails with labels above them: "coordination", "control room", "camera expert", "burst advocate", and "GRB group members". The "GRB group members" thumbnail shows a person with the name "Zhiqiu Huang" below it.

so we tried it

GRB 221009A

IACTs tried

the IACTs observed as soon as we all could (even during extremely bright moonlight ...)

```
-----  
| H.E.S.S. Shift Log 2022-10-11 |  
-----
```

```
Night: 18:04:21 - 18:38:29  
On Shift: Heiko, Kai & Ben
```

```
----> Summary
```

```
3 x GammaRayBurst_221009
```

```
----> Run List
```

```
| 1 178577 SoftTrigger CT1,2,3,4,5, Crab Nebula ra0.5393d 16:05-16:07 2min, alt 0d, rate 0Hz getting ready  
| 2 178578 Tracking CT1,2,3,4,5, GammaRayBurst_221009 17:41-17:41 0min, alt 0d, rate 0Hz  
| 3 178579 Observation CT1,2,3,4,5, GammaRayBurst_221009 ra-0.74d 18:05-18:37 32min, alt 40d, rate 824Hz 1 full normal run  
| 4 178580 MoonlightObservation CT1,2,3,4,5, GammaRayBurst_221009 dec0.7d, 18:40-18:52 12min, alt 0d, rate 0Hz cameras on small  
SubArray01/Manager: Required process (CT4/CameraTrigger) disappeared! telescopes gave up  
Node15/Receiver: CT4 has 99.3421% of missing data  
| 5 178581 MoonlightObservation CT5, GammaRayBurst_221009 dec0.70d, 18:54-19:20 26min, alt 0d, rate 0Hz  
CT5/CameraLogger: Can't contact subsystem CameraLogger via thrift! Check camera pc of CT5! camera on big telescope kept going for  
| 6 178582 PointToHorizon CT5, 19:25-19:25 0min, alt 0d, rate 0Hz another 26 min!!  
... because it was really cloudy
```

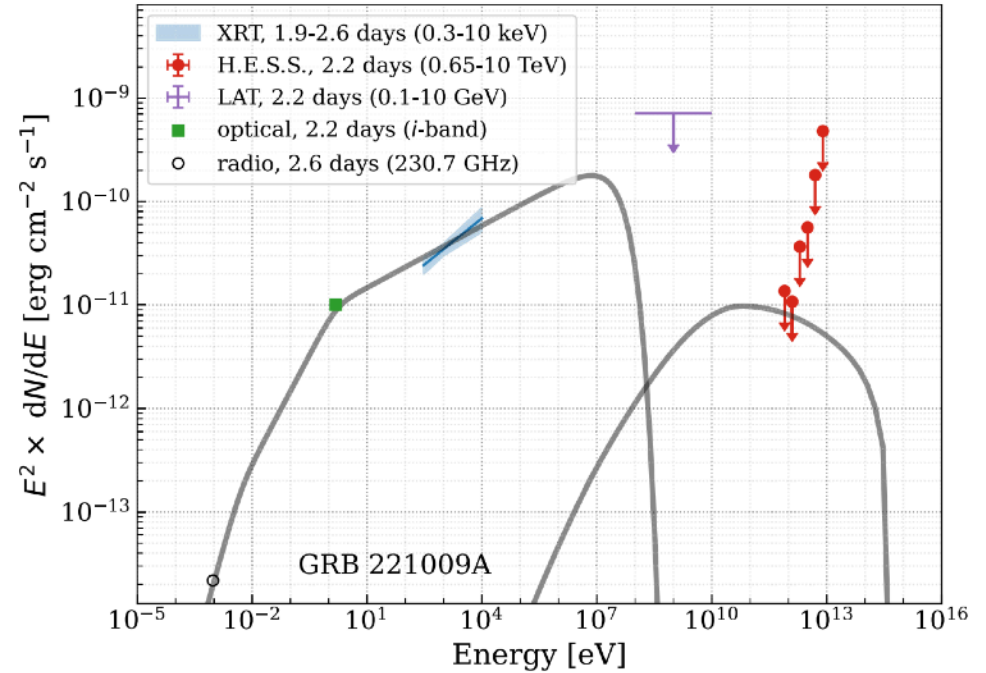
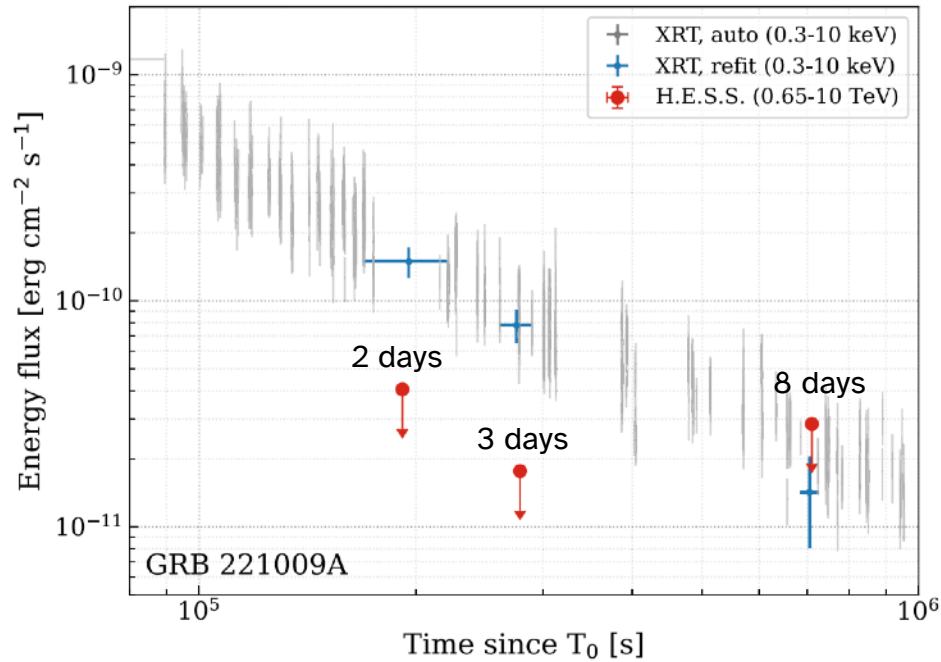
GRB 221009A

IACTs tried

the IACTs observed as soon as we all could (even during extremely bright moonlight ...)

H.E.S.S. observations

[F. Aharonian et al., ApJL 946 (2023)]



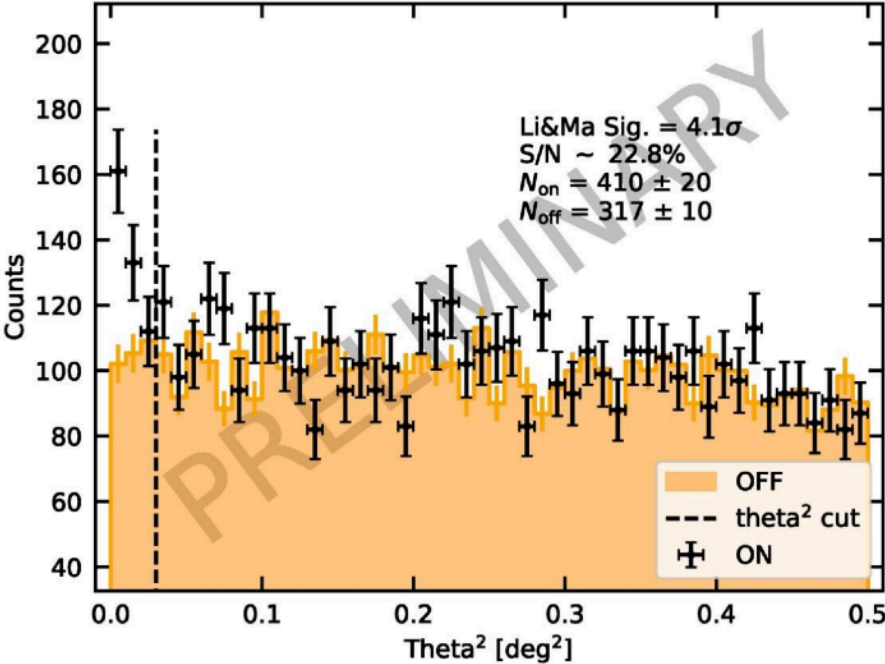
one zone SSC model

GRB 221009A

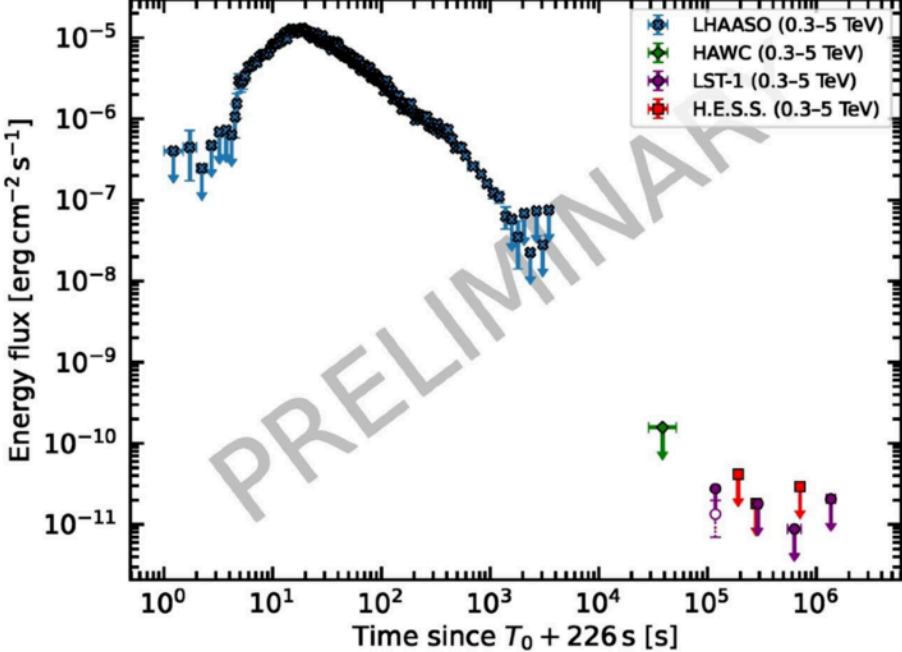
IACTs tried

the IACTs observed as soon as we all could (even during extremely bright moonlight ...)

LST-1 observations [A. Aguasca-Cabot, Gamma 2024]



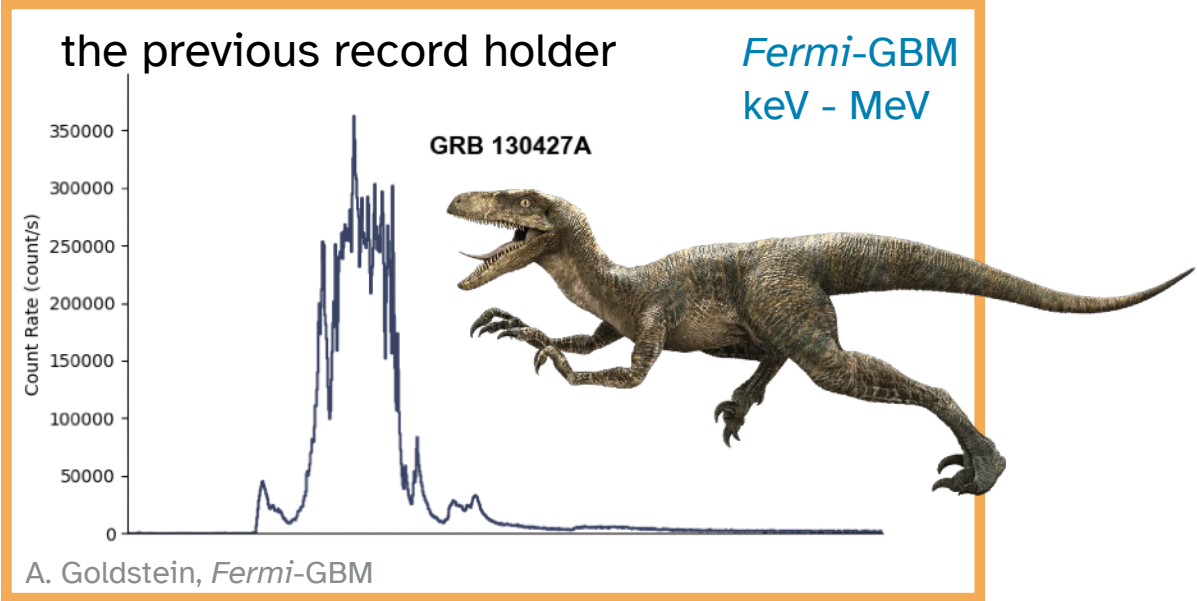
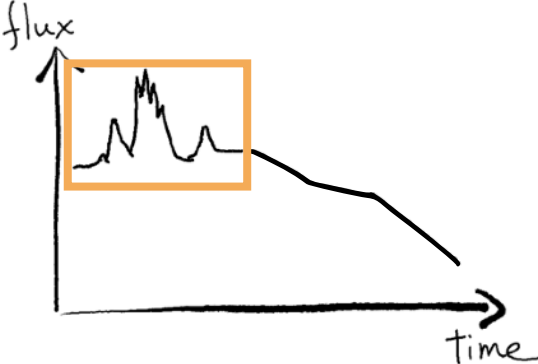
θ^2 -plot for the moon data (Oct. 10)



LST-1 light curve using moon and dark data

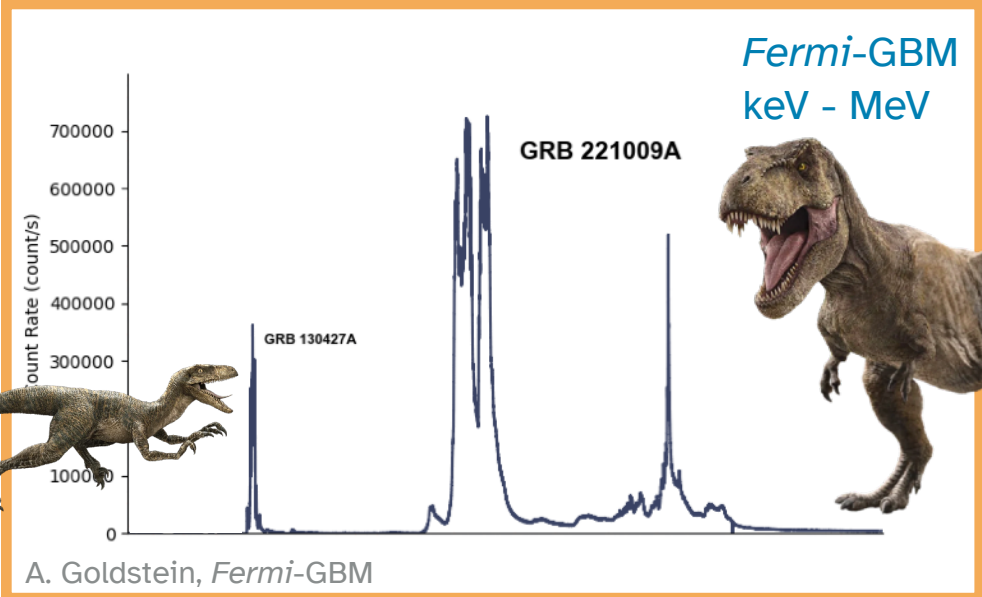
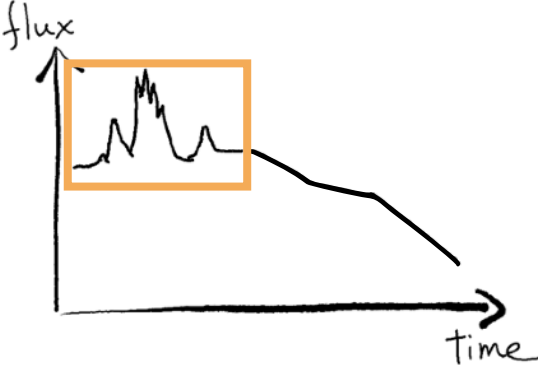
GRB 221009A

the BOAT (“Brightest of All Time”)



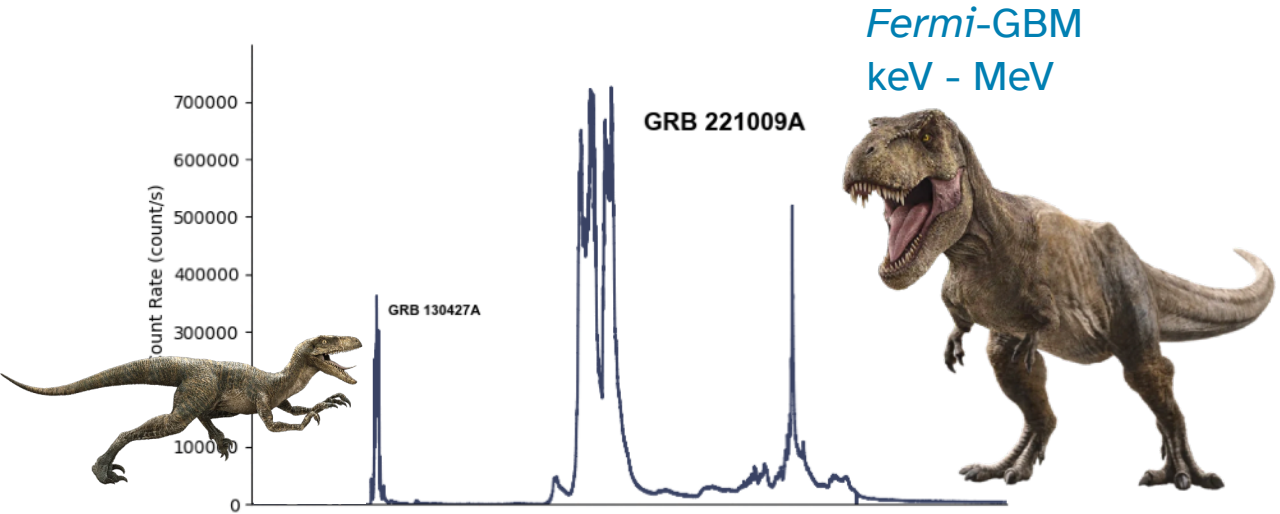
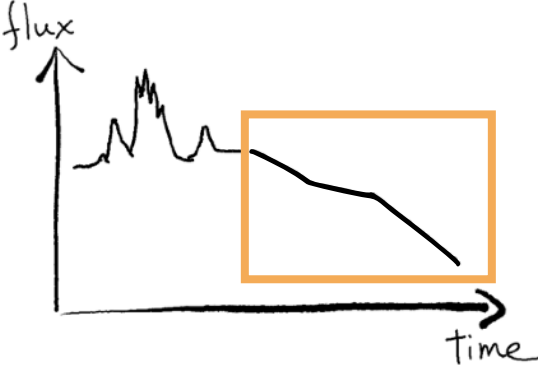
GRB 221009A

the BOAT (“Brightest of All Time”)

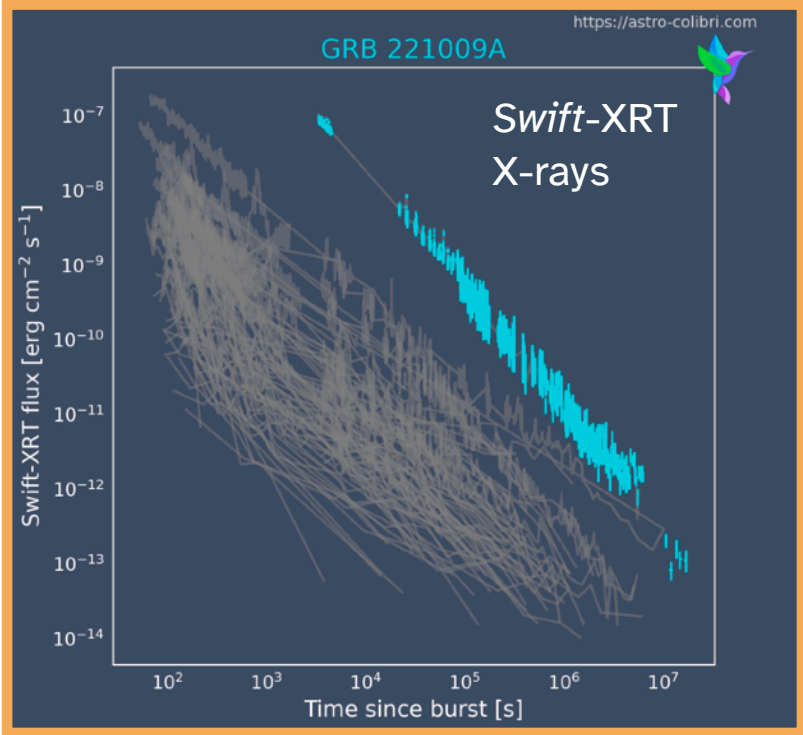


GRB 221009A

the BOAT (“Brightest of All Time”)



A. Goldstein, *Fermi*-GBM

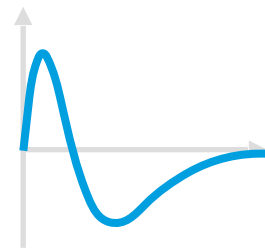
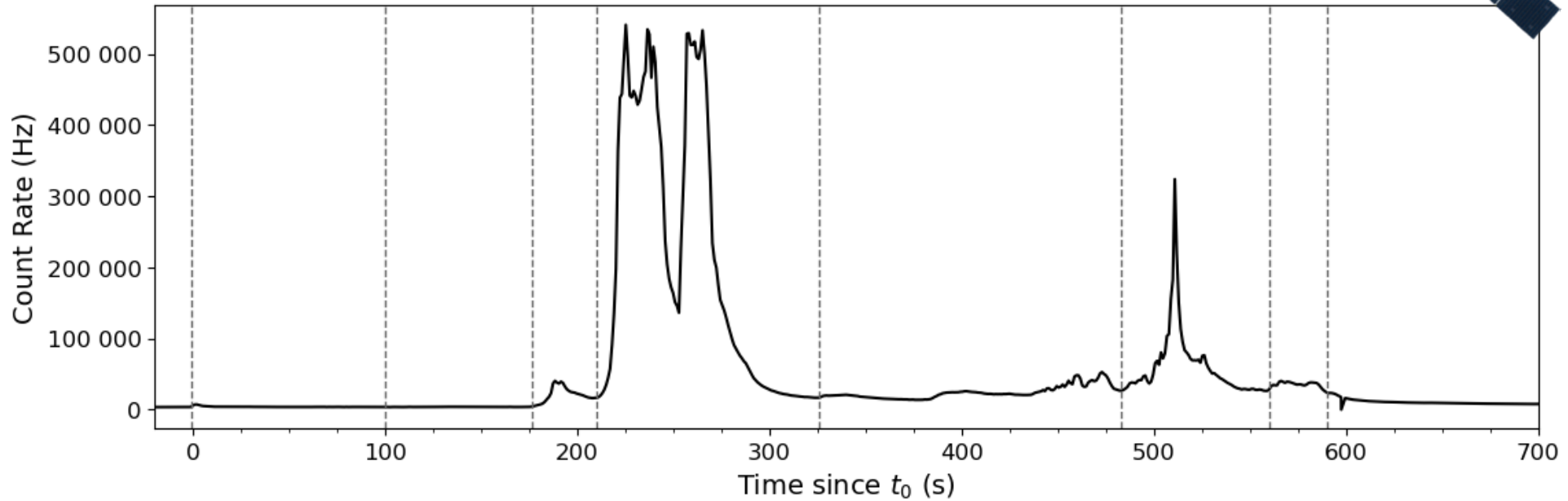
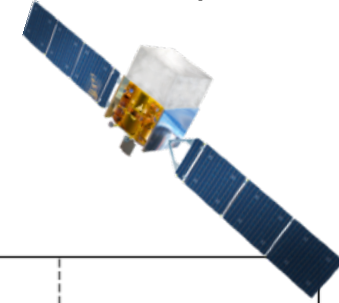


GRB 221009A

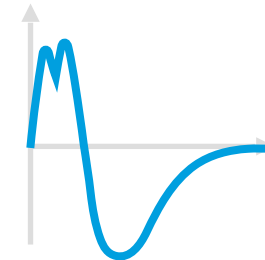
Too much of a good thing

The prompt emission was so bright that it caused problems for the detectors
e.g.: photons were hitting the detectors faster than the signals could be read out

Fermi-GBM (keV - MeV)



pulse pileup



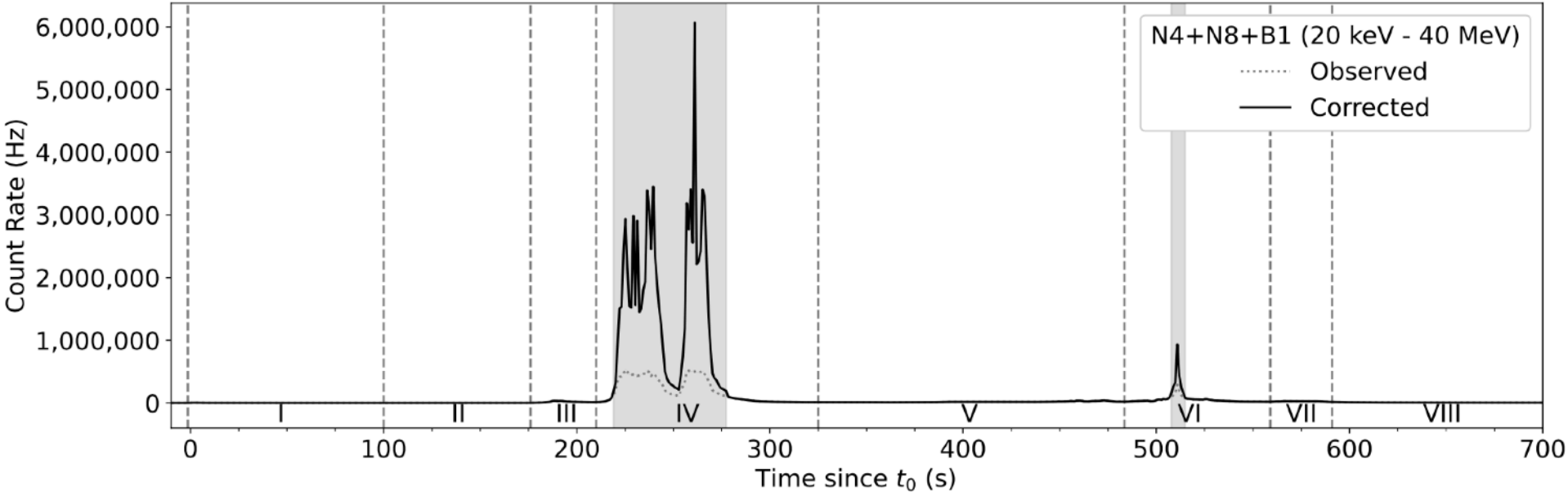
[V. Chaplin, NIMPA 717 (2013)]

GRB 221009A

Too much of a good thing

The prompt emission was so bright that it caused problems for the detectors
e.g.: photons were hitting the detectors faster than the signals could be read out

Fermi-GBM (keV - MeV)

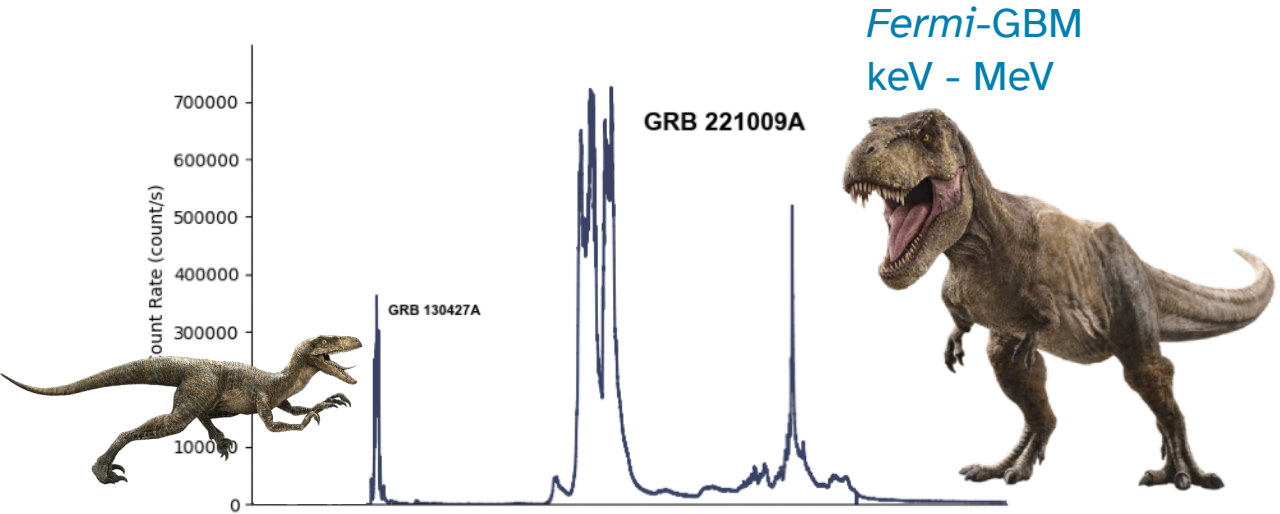
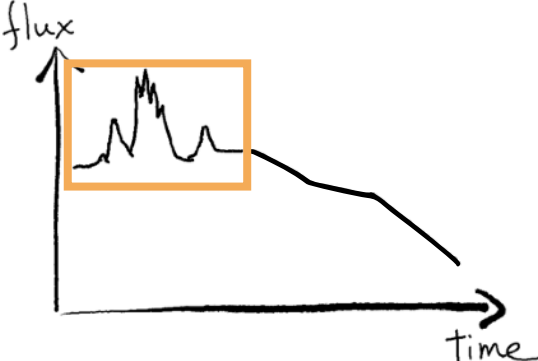


[S. Lesage et al., ApJL 592 (2023)]

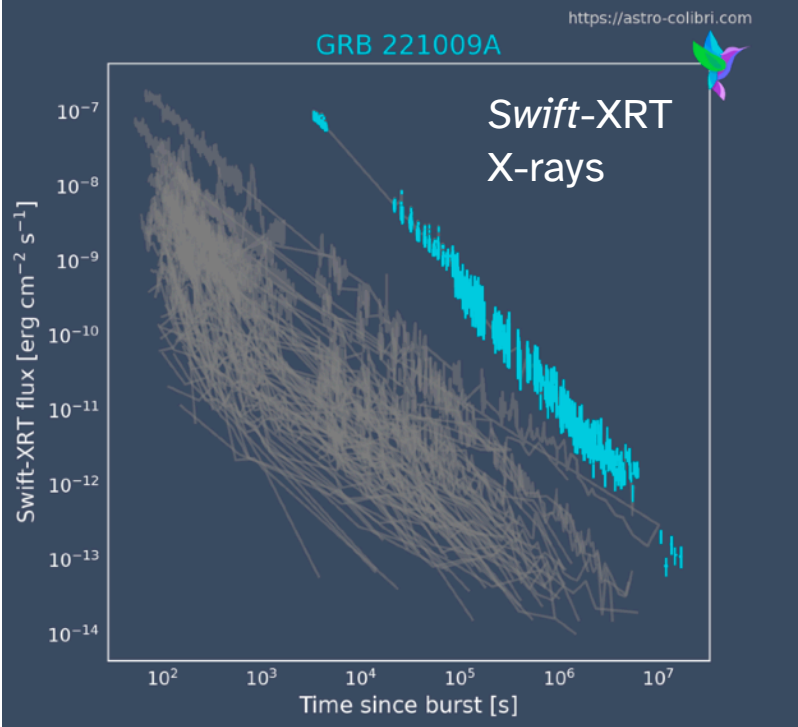
The corrected light curve was even more extraordinary

GRB 221009A

the BOAT (“Brightest of All Time”)

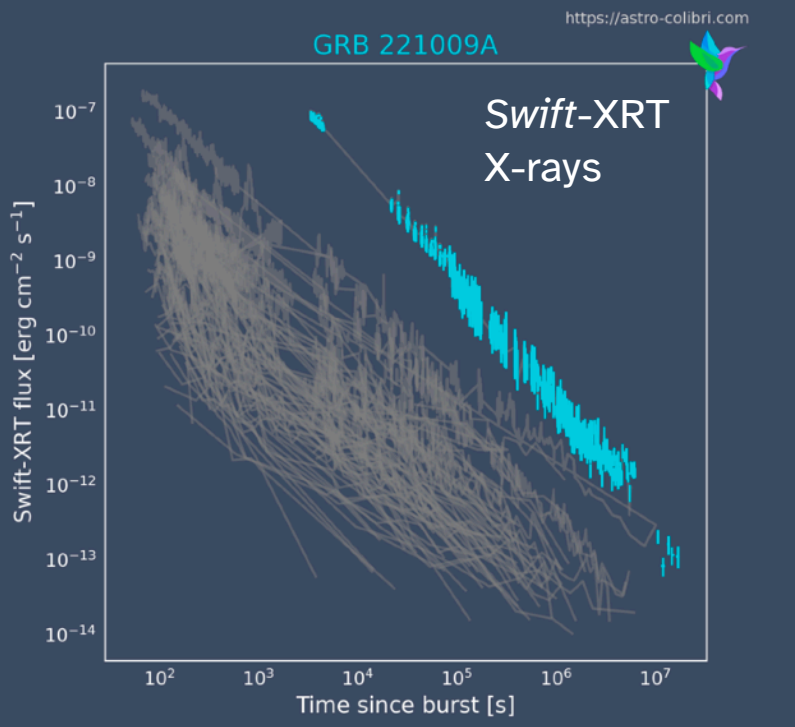
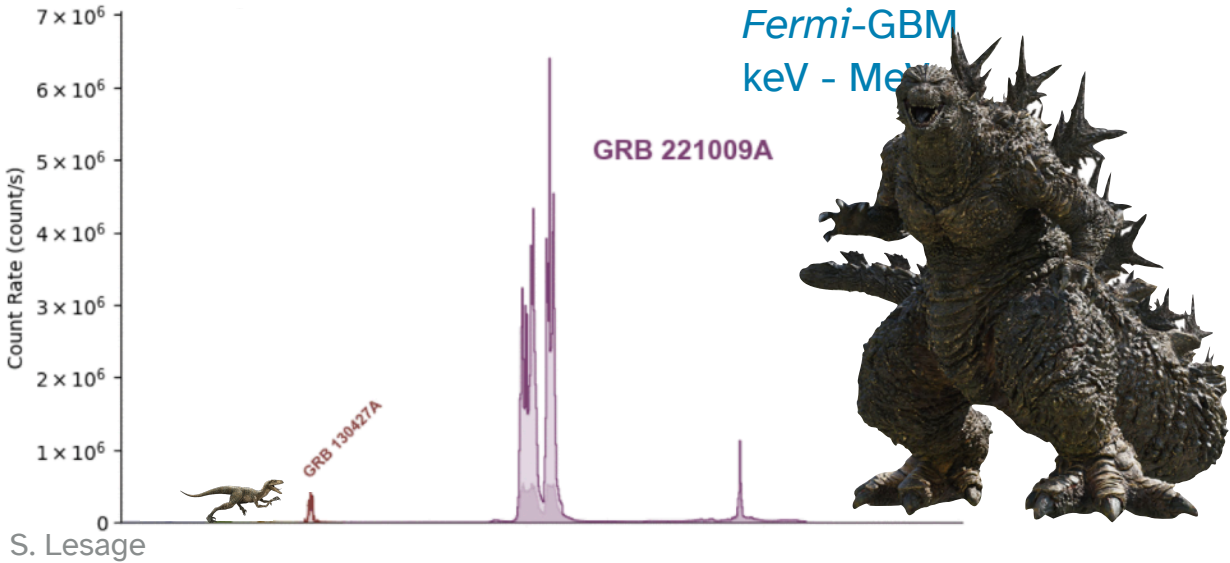
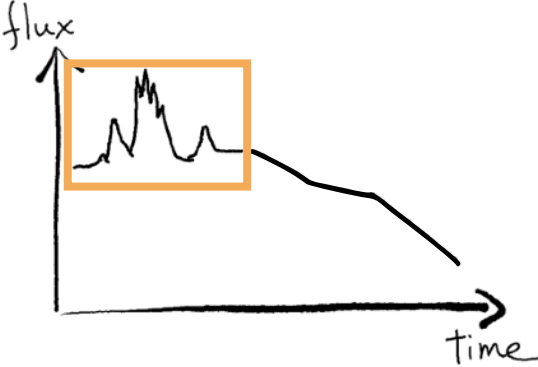


A. Goldstein, *Fermi*-GBM



GRB 221009A

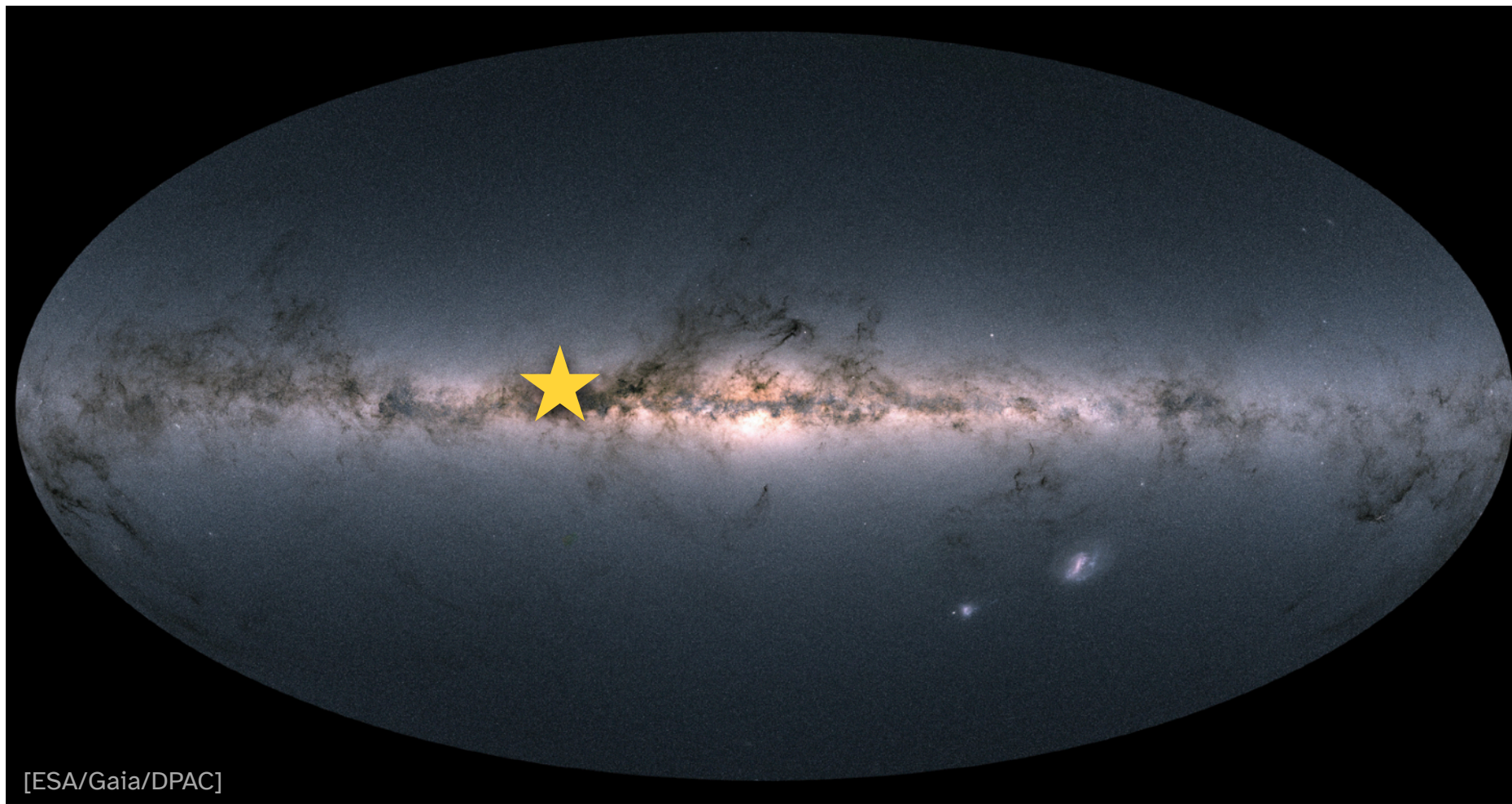
the BOAT (“Brightest of All Time”)



GRB 221009A

the BOAT (“Brightest of All Time”)

GRB 221009A was at very low Galactic latitudes



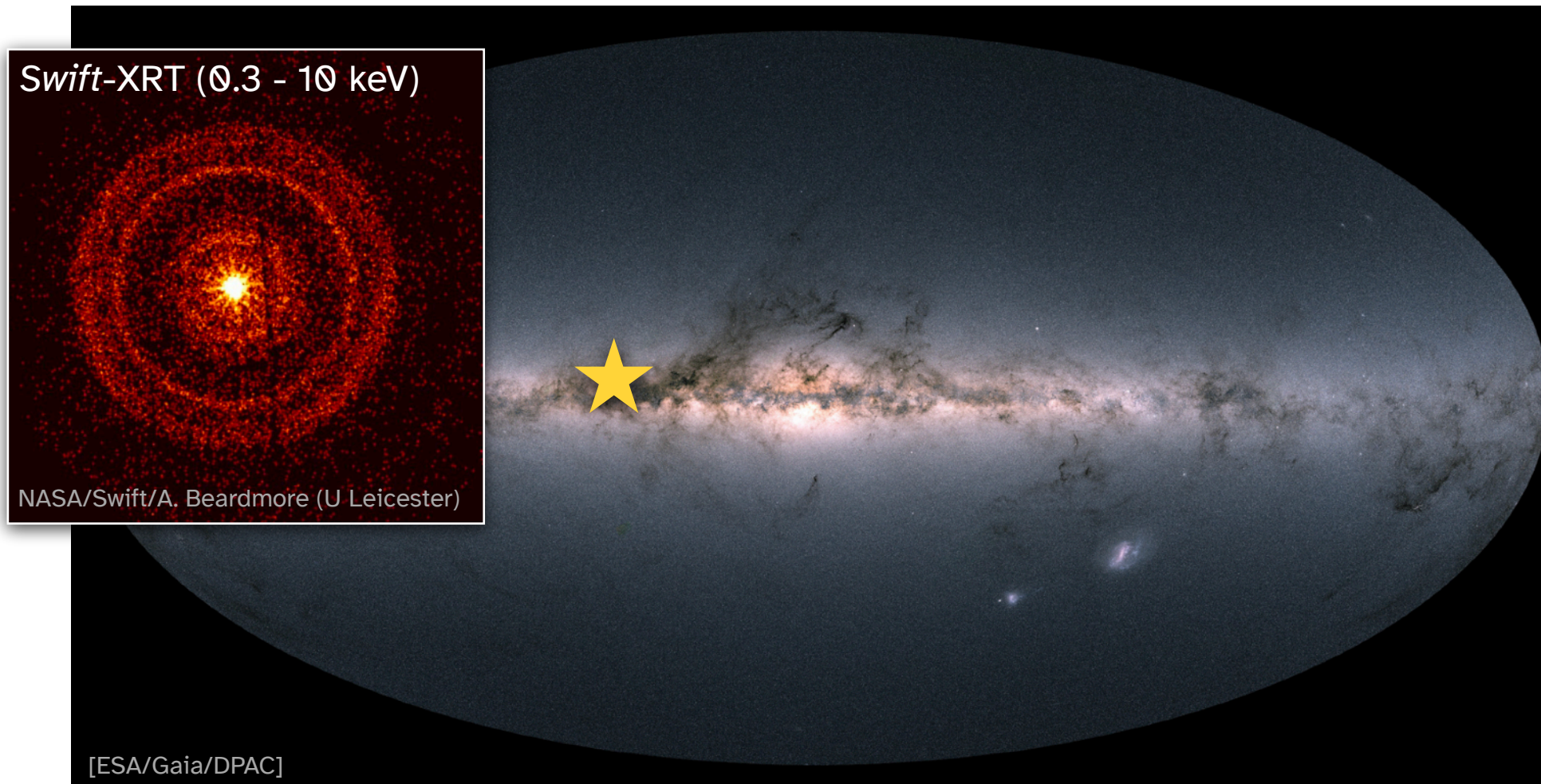
GRB 221009A

the BOAT (“Brightest of All Time”)

GRB 221009A was at very low Galactic latitudes -> X-ray telescopes saw *dust rings*



[G. Vasilopoulos et al., MNRAS 521 (2023)]

[A. Tiengo et al., ApJL 946 (2023)]



VHE gamma-ray detectors

MAGIC



[Derek Strom, Giovanni Ceribella, MAGIC Collaboration]

LST-1



CTAO

[Otger Ballester (IFAE)]

VERITAS



VERITAS Collaboration

LHAASO



[IHEP]



高海拔宇宙线观测站

HAWC



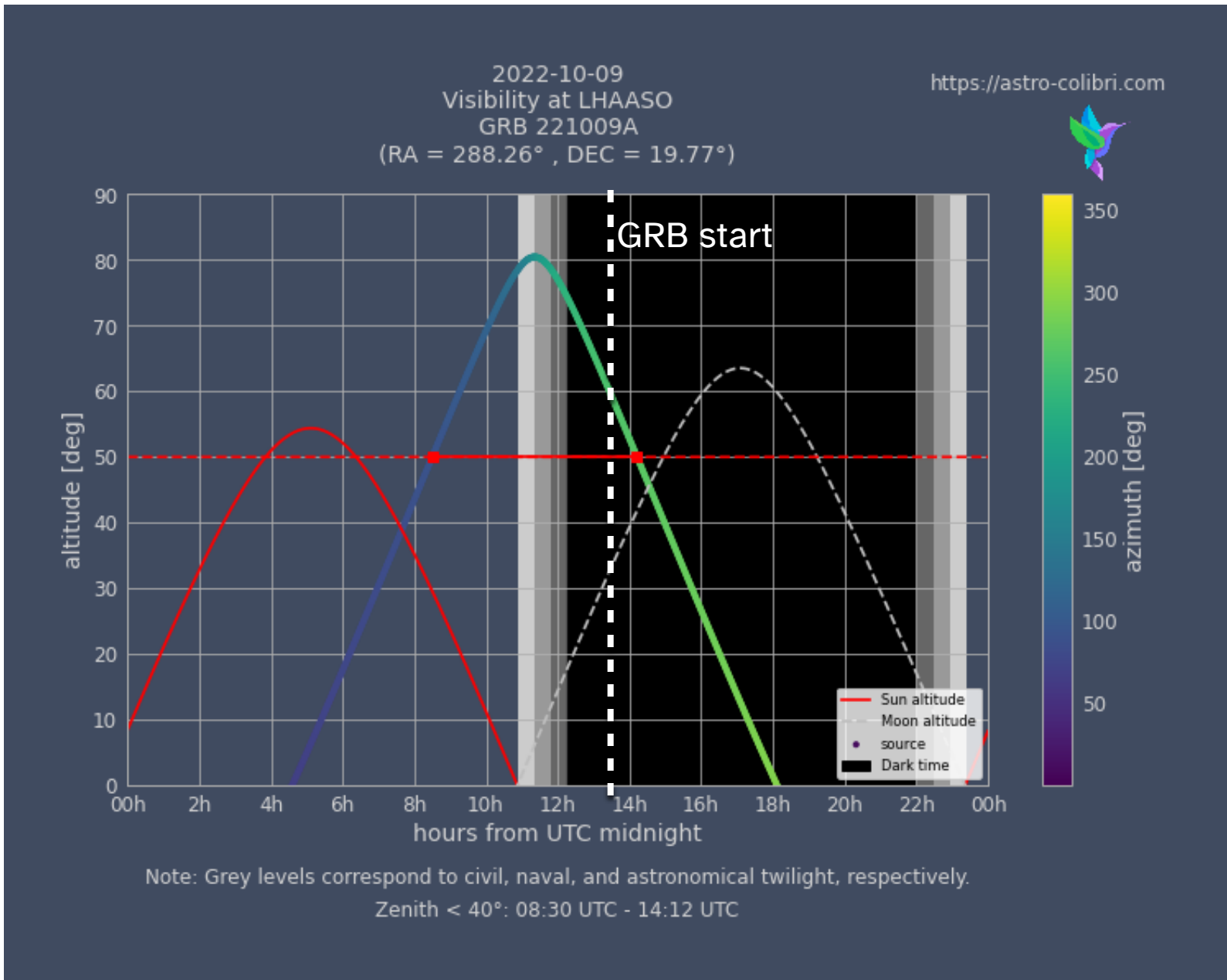
[J. Goodman]

H.E.S.S.

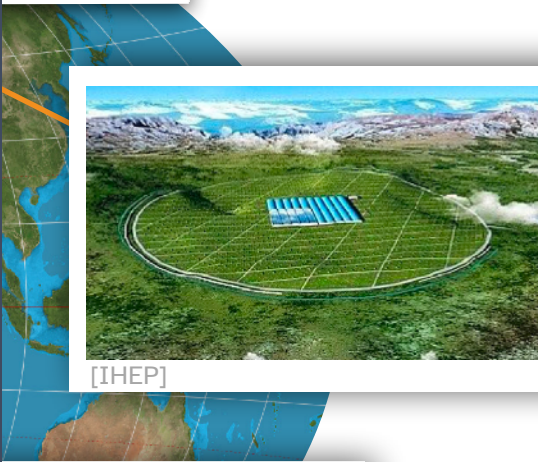


[H.E.S.S., MPIK/Christian Föhr]

V



LST-1
CTAO



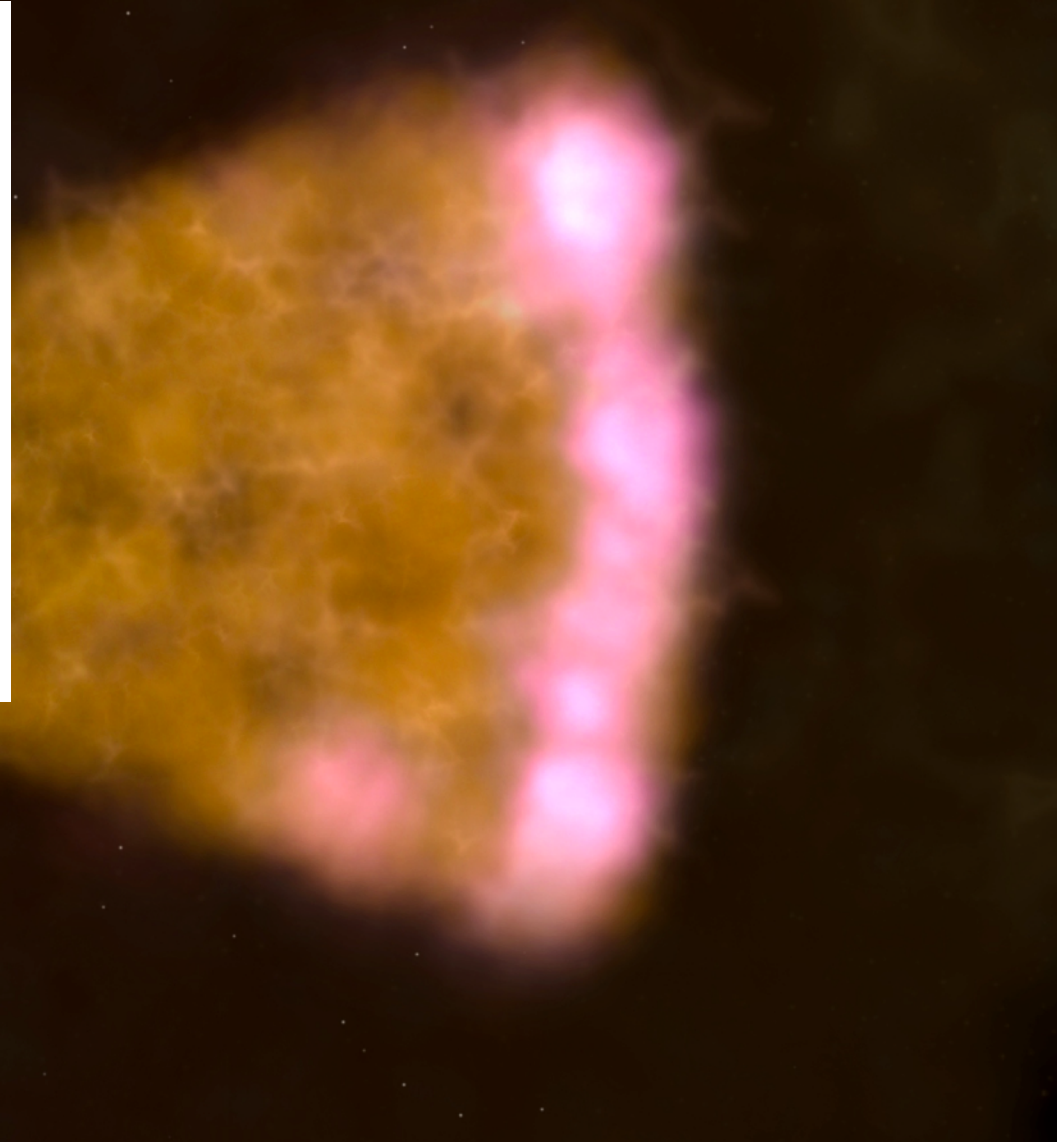
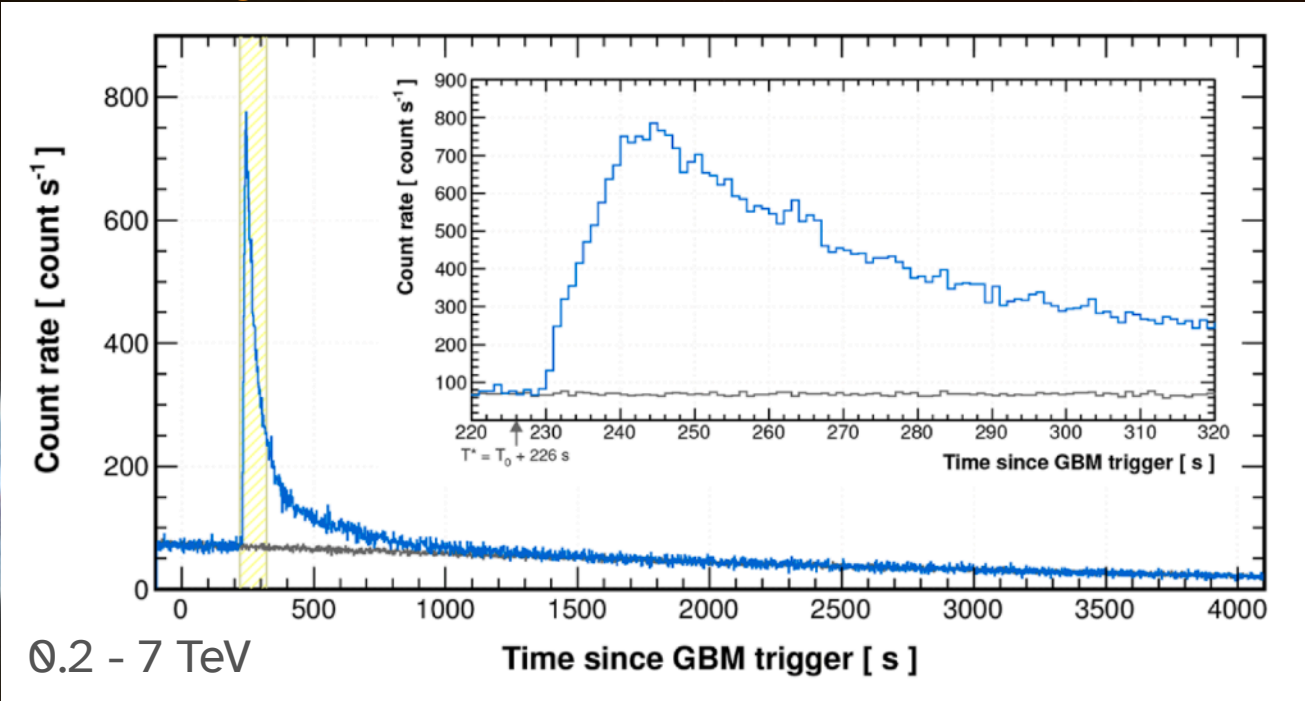
[Daniel R. Strebe]

GRB 221009A

the BOAT (“Brightest of All Time”)

the record-breaking LHAASO detection

[LHAASO Collaboration, Science 380 (2023)]

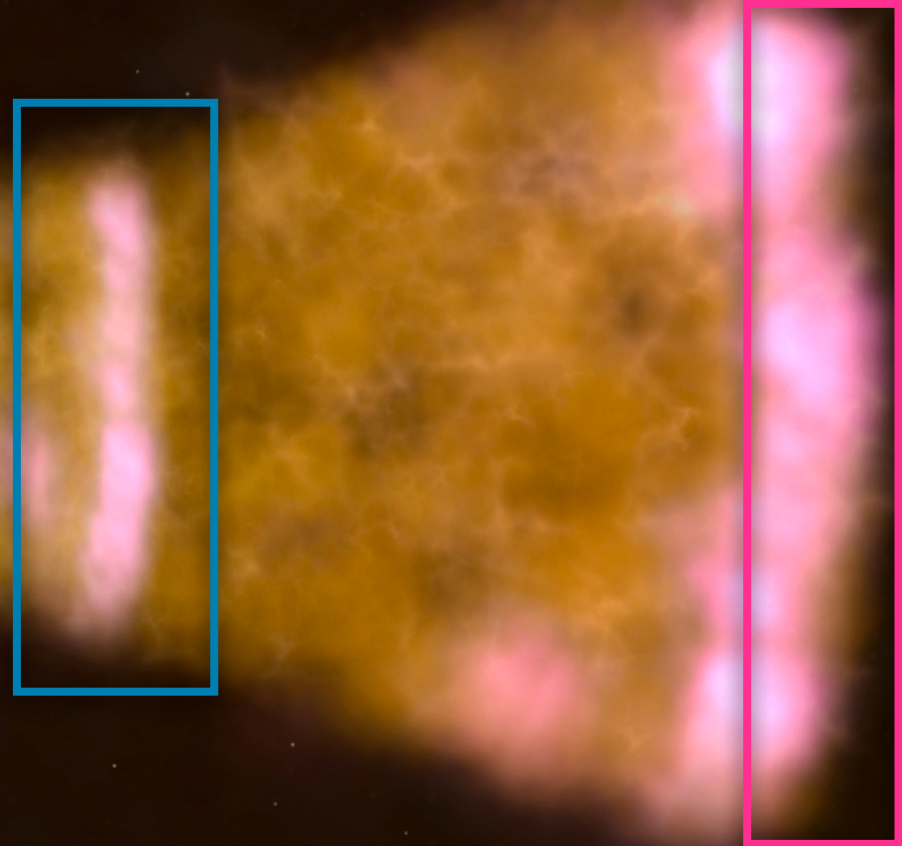
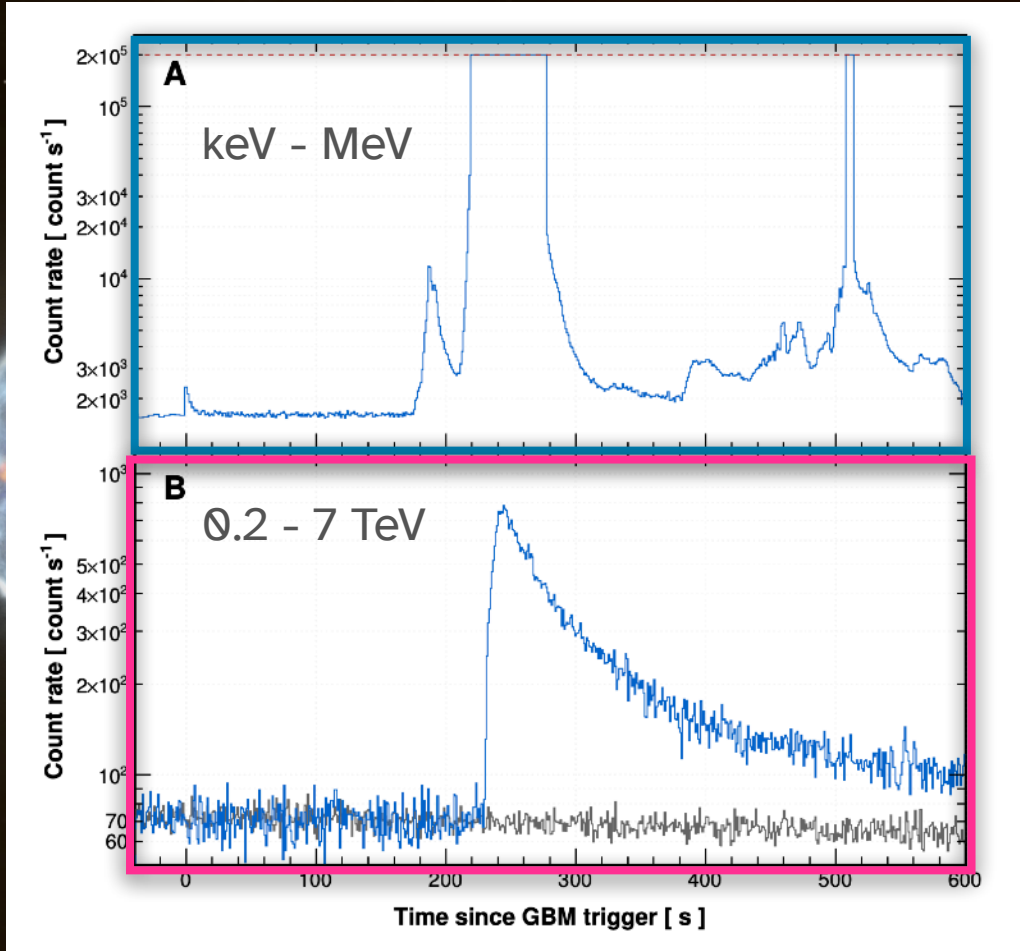


GRB 221009A

the BOAT (“Brightest of All Time”)

the record-breaking LHAASO detection

[LHAASO Collaboration, Science 380 (2023)]

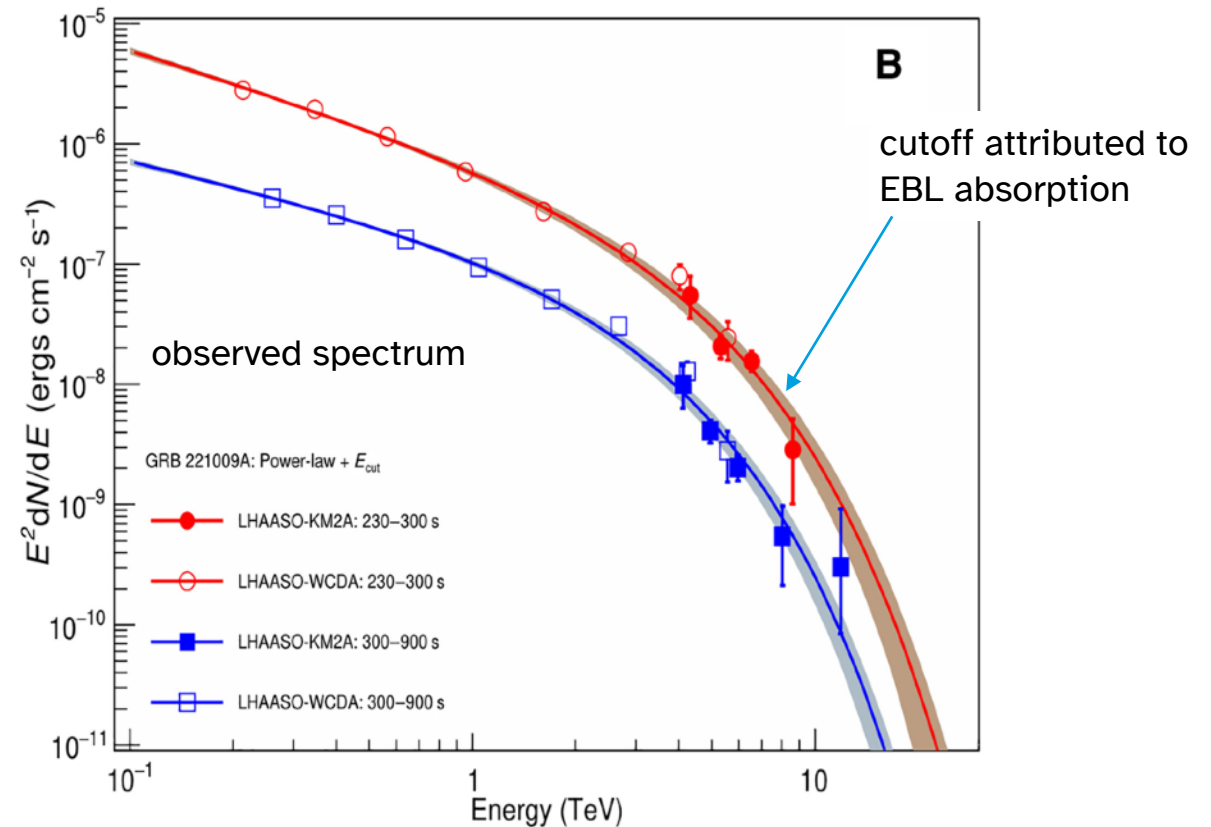
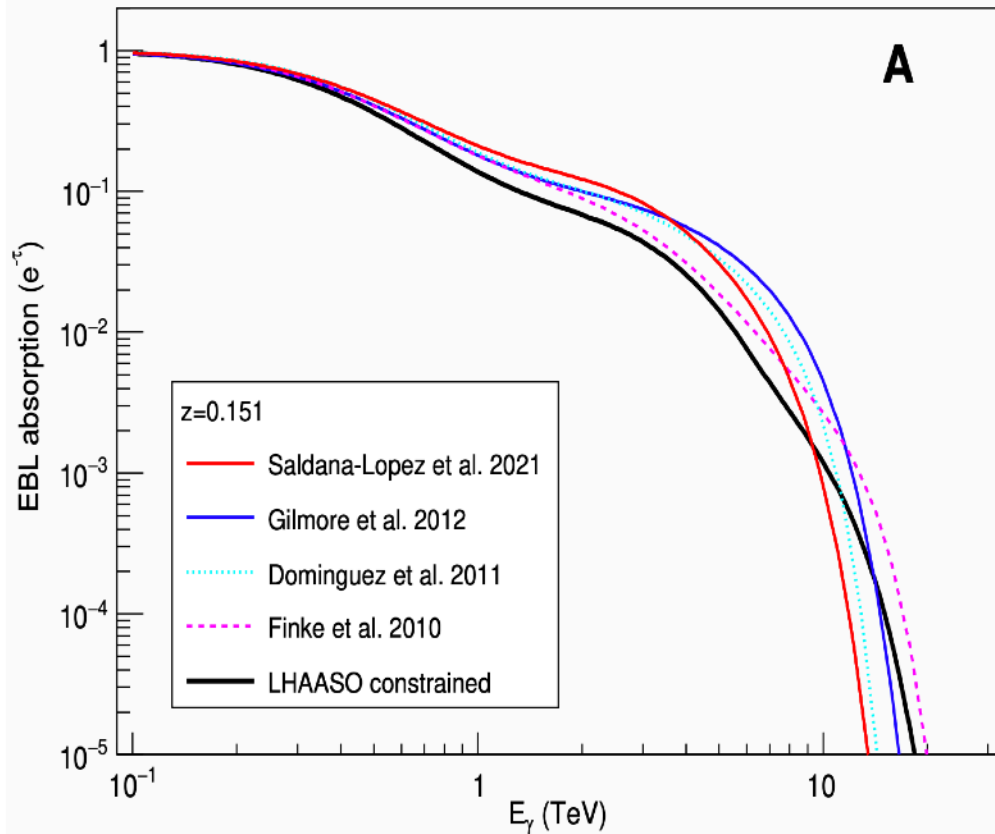


GRB 221009A

the BOAT (“Brightest of All Time”)

For a redshift of 0.151, the EBL absorption has a large effect at $E > 10$ TeV and the **uncertainty** in the EBL is also very important!

[Z. Cao et al., Science Advances 9 (2023)]



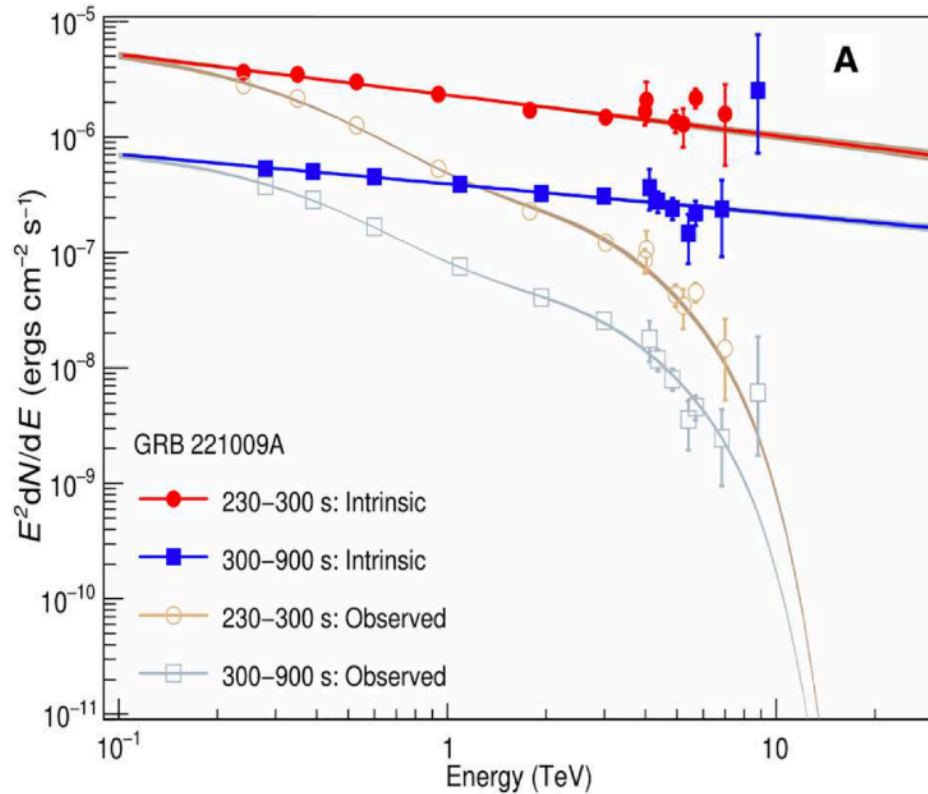
GRB 221009A

the BOAT (“Brightest of All Time”)

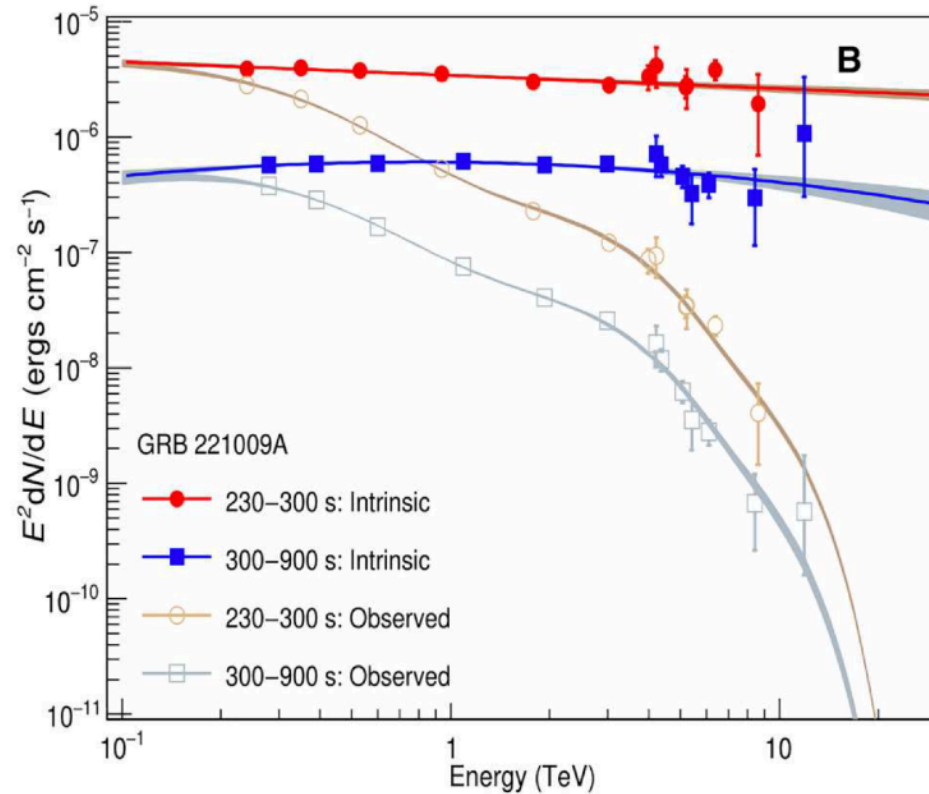
For a redshift of 0.151, the EBL absorption has a large effect at $E > 10$ TeV and the **uncertainty** in the EBL is also very important!

[Z. Cao et al., Science Advances 9 (2023)]

assuming an EBL model (Saldana-Lopez et al. 2021)



rescaling the EBL model at different wavelengths

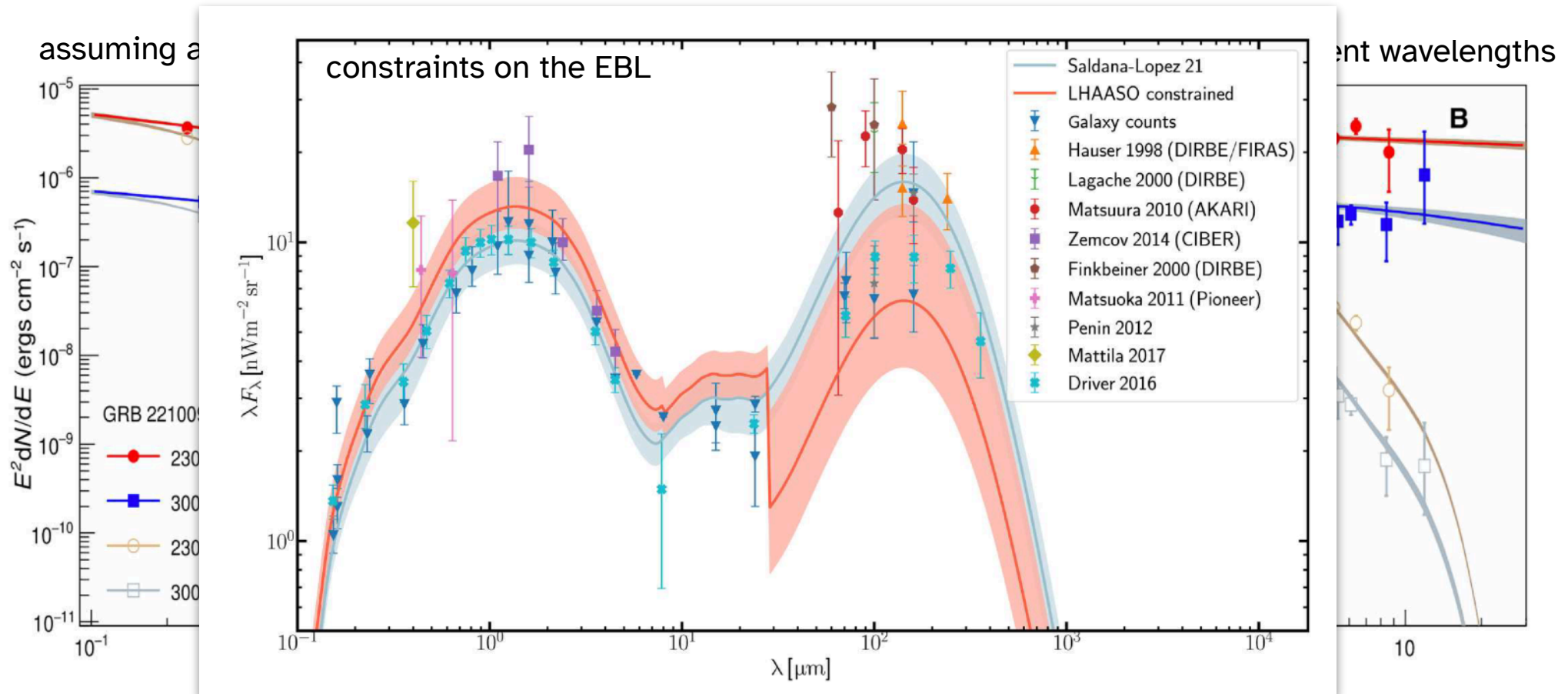


GRB 221009A

the BOAT (“Brightest of All Time”)

For a redshift of 0.151, the EBL absorption has a large effect at $E > 10$ TeV and the **uncertainty** in the EBL is also very important!

[Z. Cao et al., Science Advances 9 (2023)]



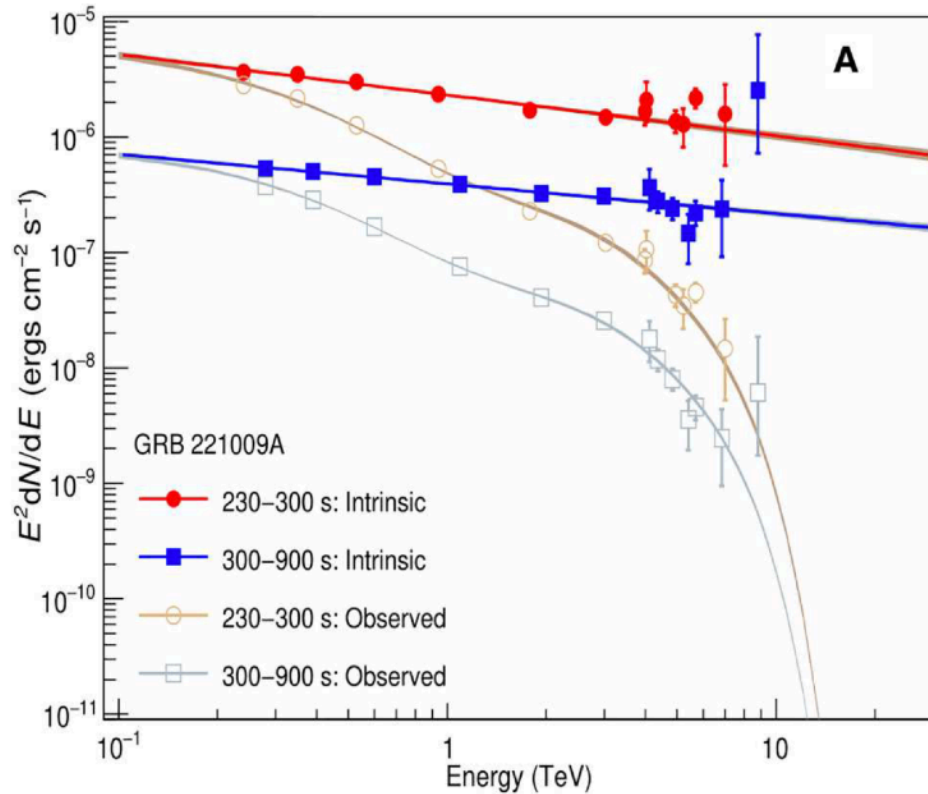
GRB 221009A

the BOAT (“Brightest of All Time”)

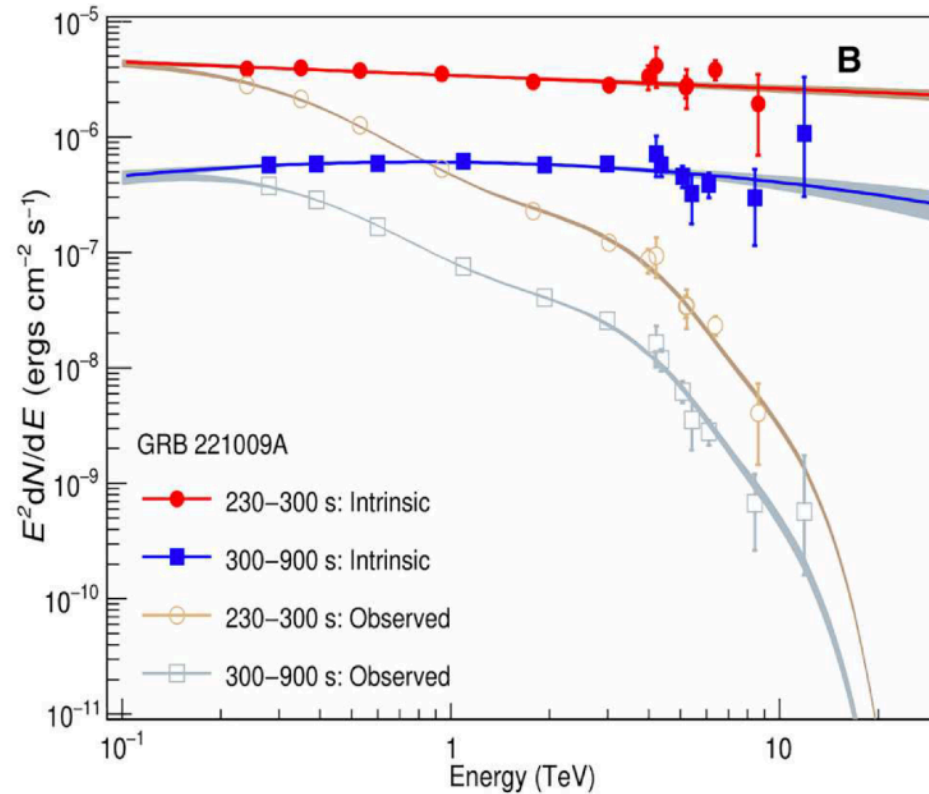
For a redshift of 0.151, the EBL absorption has a large effect at $E > 10$ TeV and the **uncertainty** in the EBL is also very important!

[Z. Cao et al., Science Advances 9 (2023)]

assuming an EBL model (Saldana-Lopez et al. 2021)



rescaling the EBL model at different wavelengths

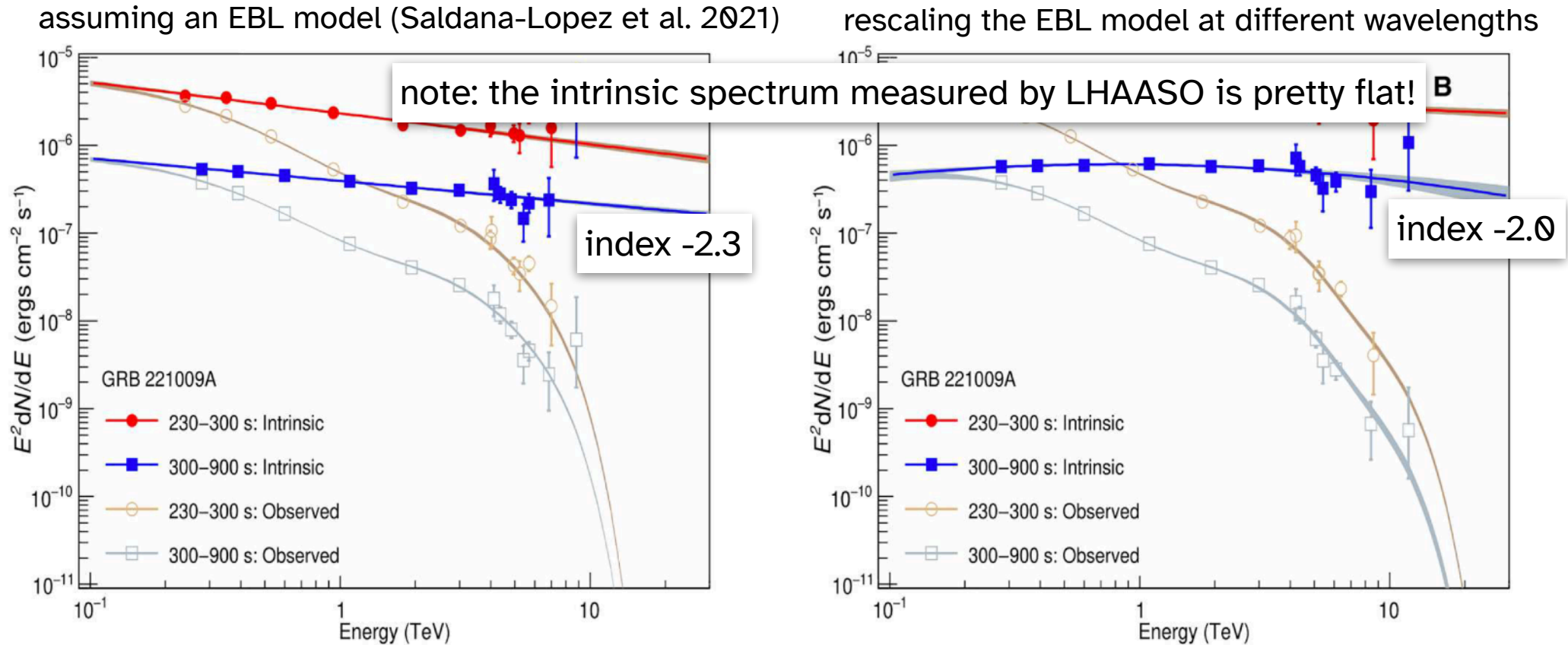


GRB 221009A

the BOAT (“Brightest of All Time”)

For a redshift of 0.151, the EBL absorption has a large effect at $E > 10$ TeV and the **uncertainty** in the EBL is also very important!

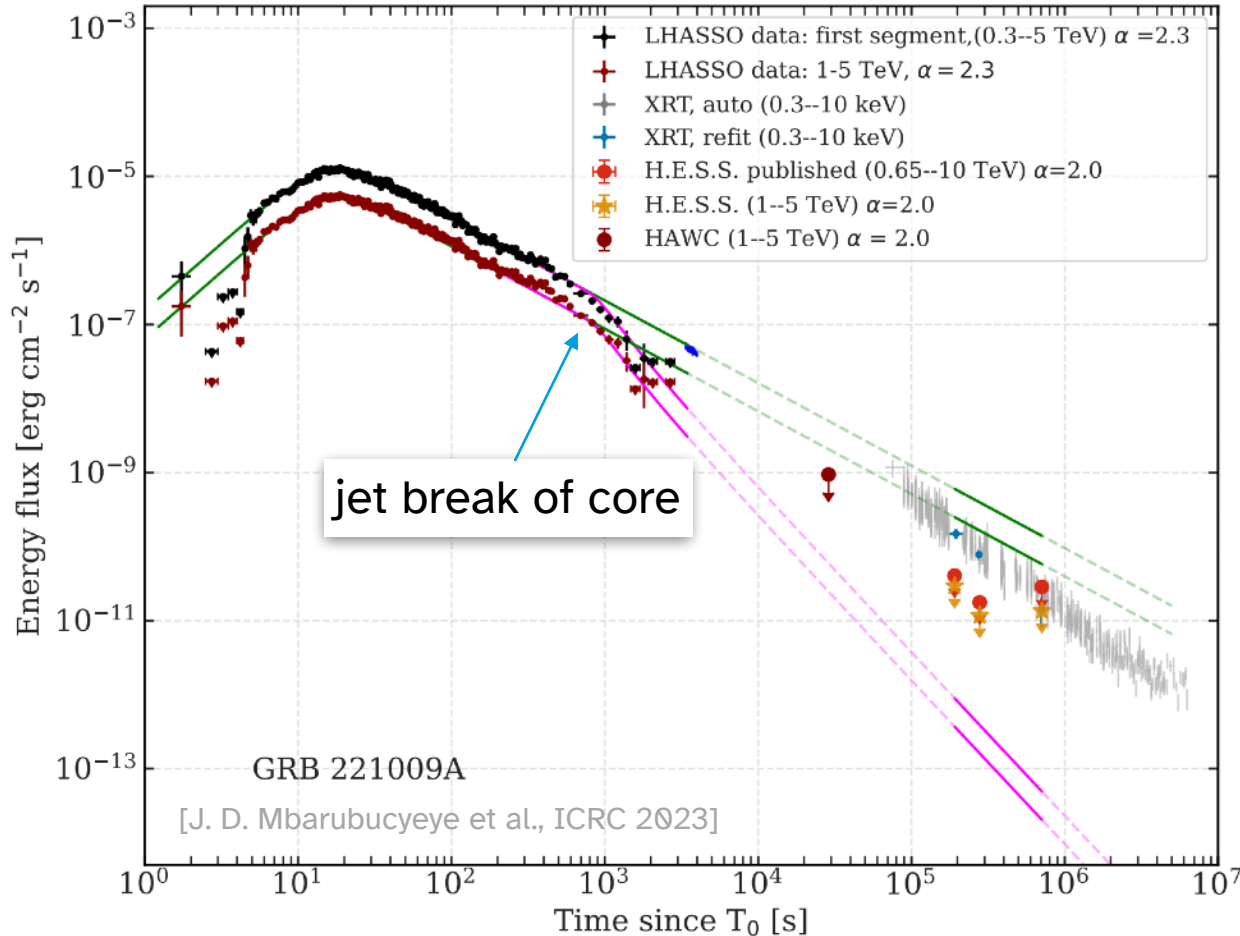
[Z. Cao et al., Science Advances 9 (2023)]



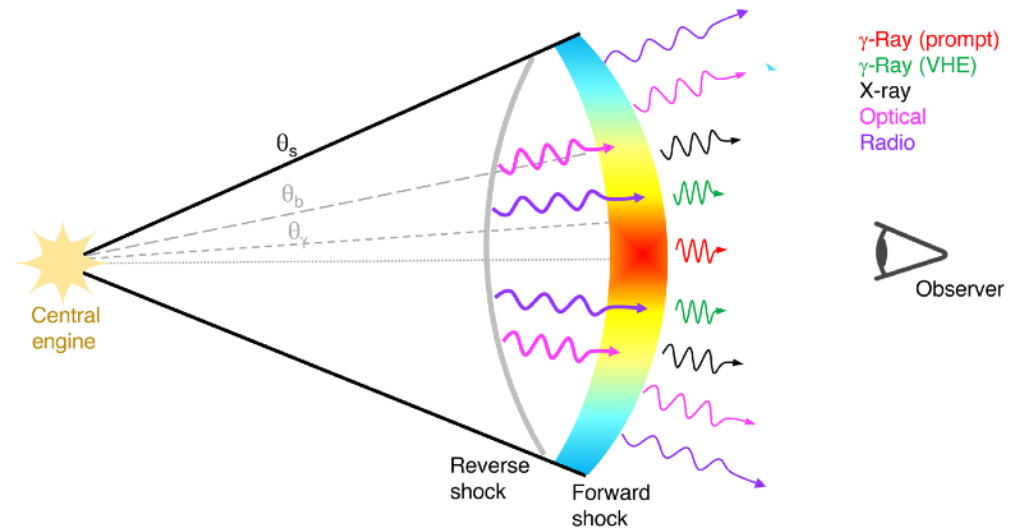
GRB 221009A

the BOAT (“Brightest of All Time”)

The bigger MWL picture:



[B. O'Connor et al., Science Advances 9 (2023)]



Most likely a **structured jet**:

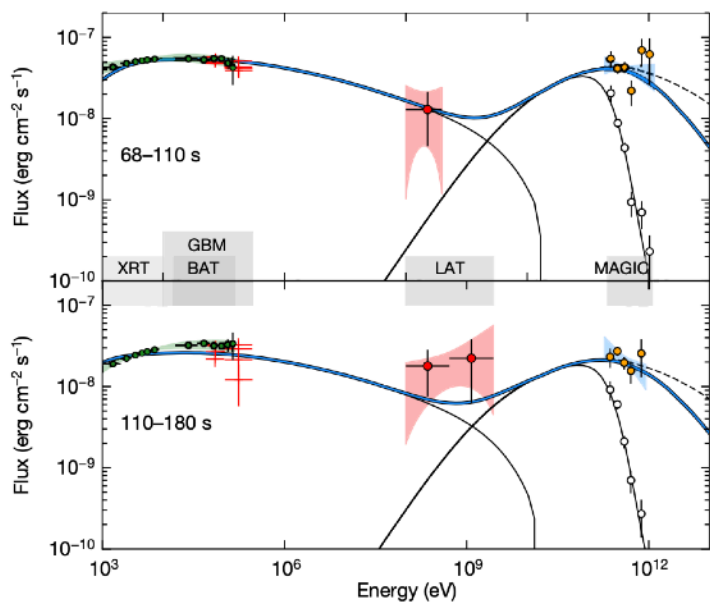
- narrow, high Γ core
- lower Γ wings

So, do we see the inverse Compton component in VHE GRBs?

The three best test cases (imo)

GRB 190114C

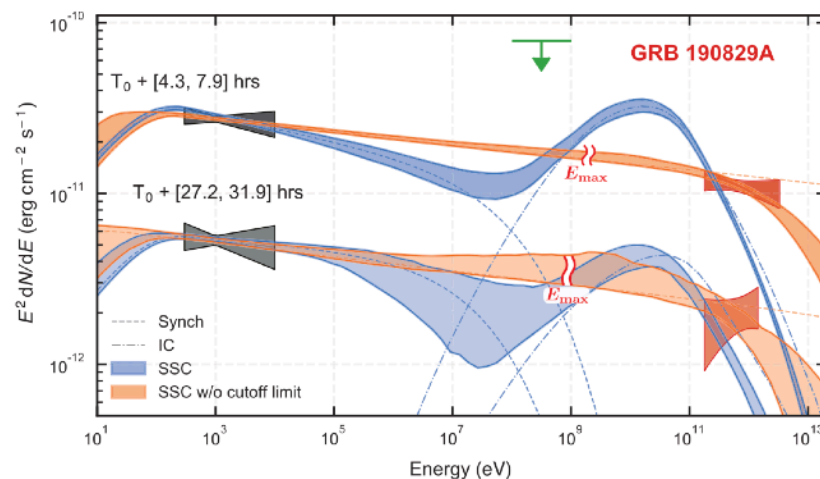
[MAGIC, Nature 575 (2019)]



“yes”

GRB 190829A

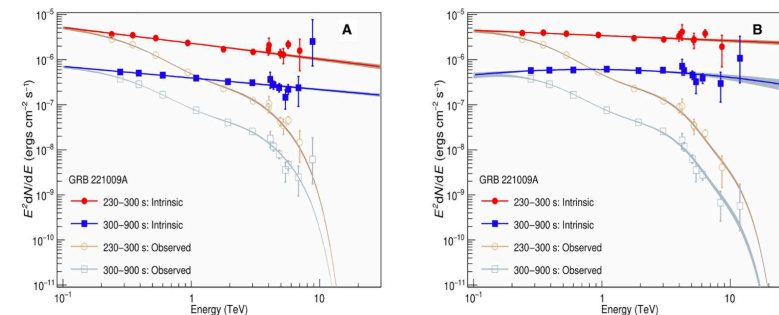
[H.E.S.S. et al., Science 372 (2021)]



“no”

GRB 221009A

[LHAASO, Science Advances 9 (2023)]



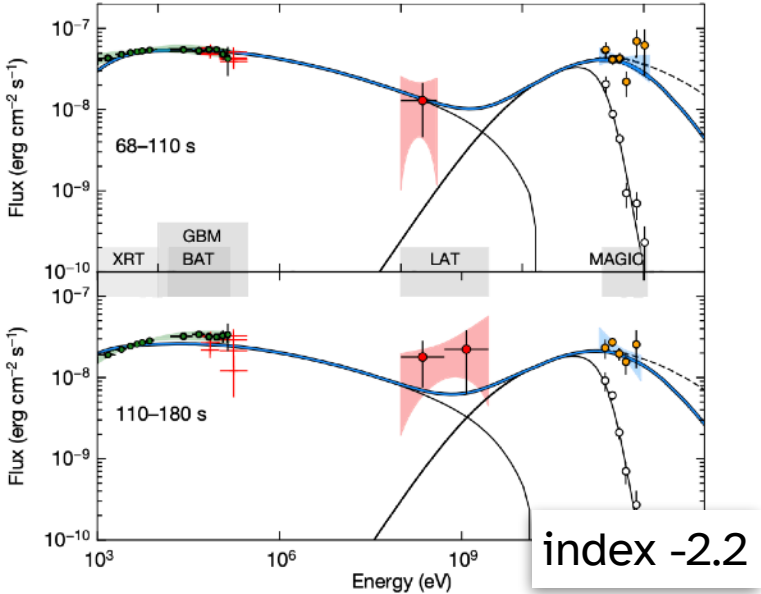
“no”

So, do we see the inverse Compton component in VHE GRBs?

The three best test cases (imo)

GRB 190114C

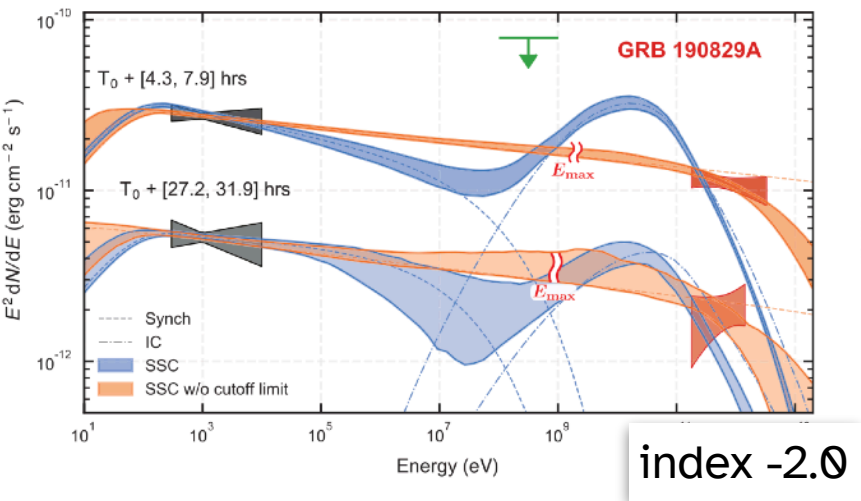
[MAGIC, Nature 575 (2019)]



“yes?”

GRB 190829A

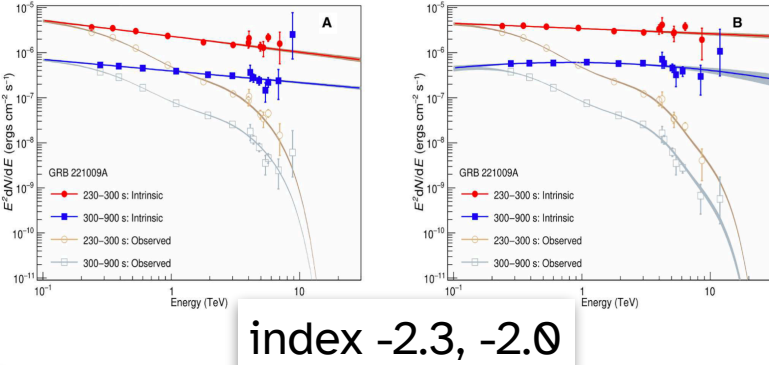
[H.E.S.S. et al., Science 372 (2021)]



“no”

GRB 221009A

[LHAASO, Science Advances 9 (2023)]

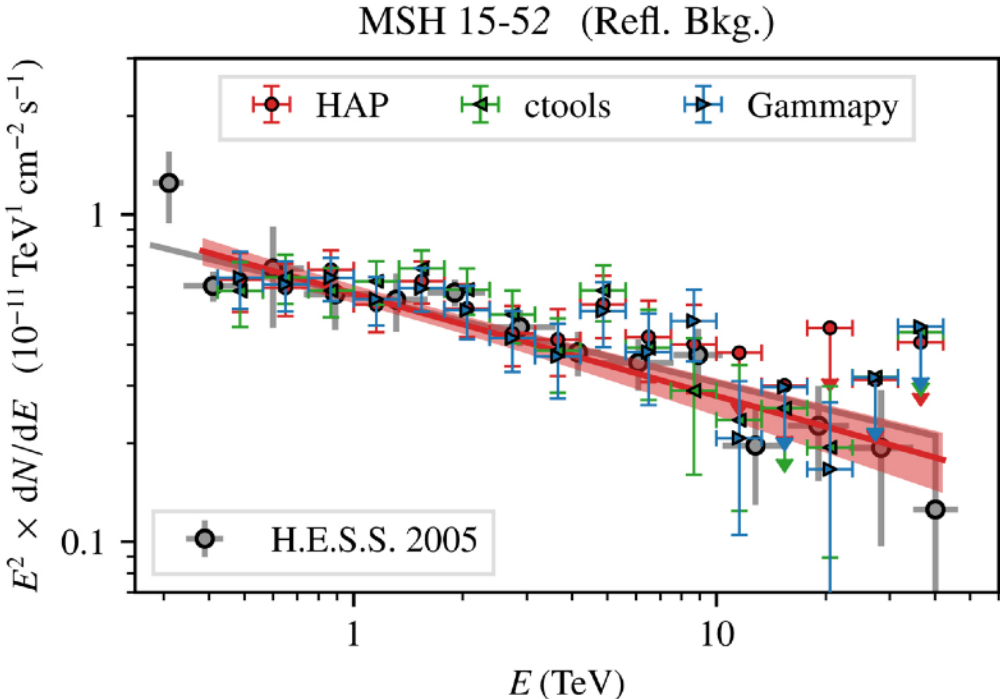


“no”

Pause to talk about systematic uncertainties

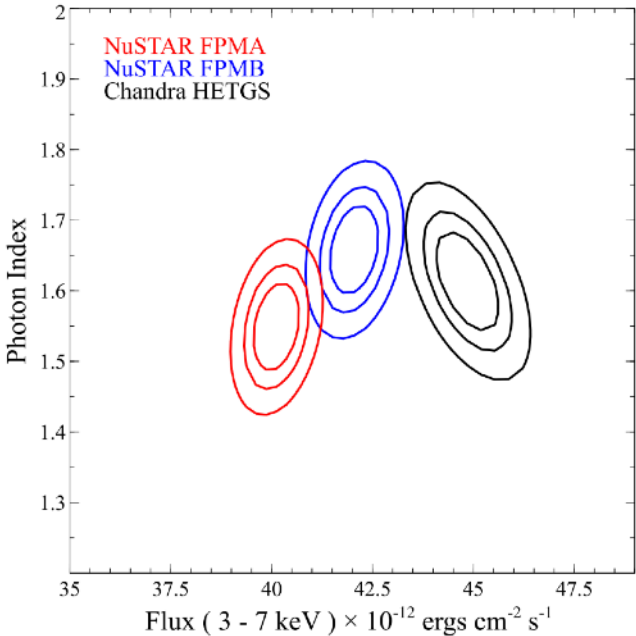
How well are we reconstructing the data? How much do we believe our reconstruction?

different reconstruction pipelines, analysis choices, or software can give different results



[L. Mohrmann et al., A&A 632 (2019)]

different telescopes have their own systematic uncertainties



[K. K. Madsen et al., Astro J 153 (2017)]

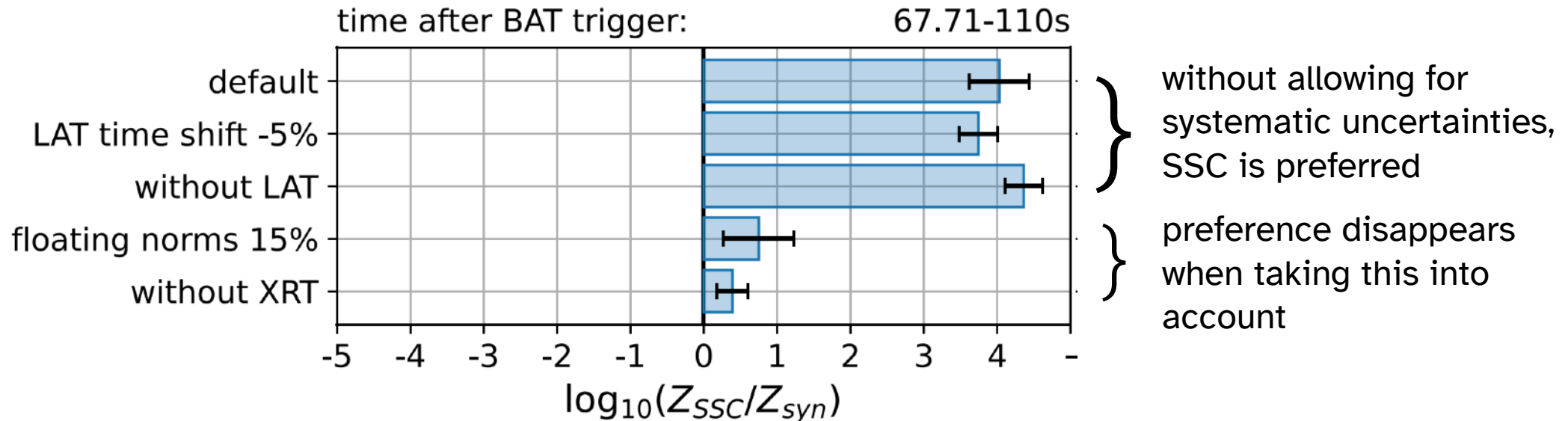
Do we see the inverse Compton component in VHE GRBs?

Systematic uncertainties

Allowing for systematic uncertainties (esp. between instruments) can make a big difference in your result

[M. Klinger et al., MNRAS 520 (2023)]

disclaimer: I'm on this paper

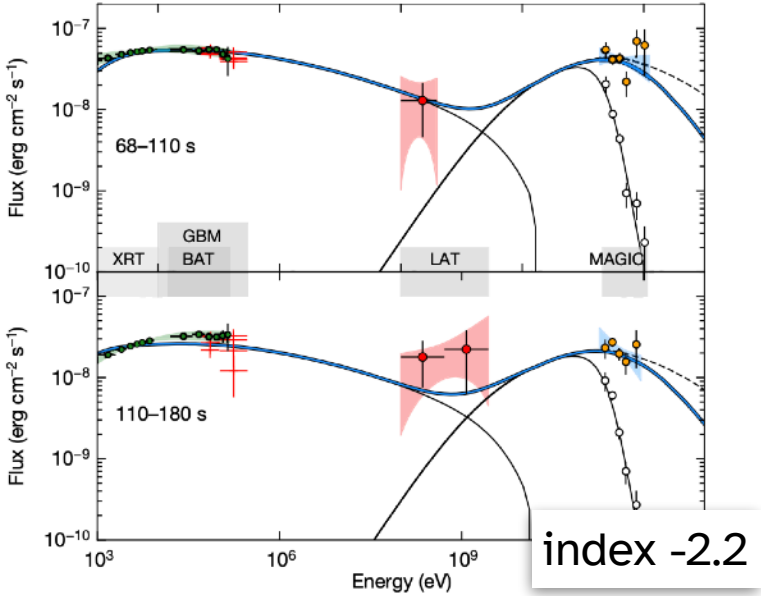


So, do we see the inverse Compton component in VHE GRBs?

The three best test cases (imo)

GRB 190114C

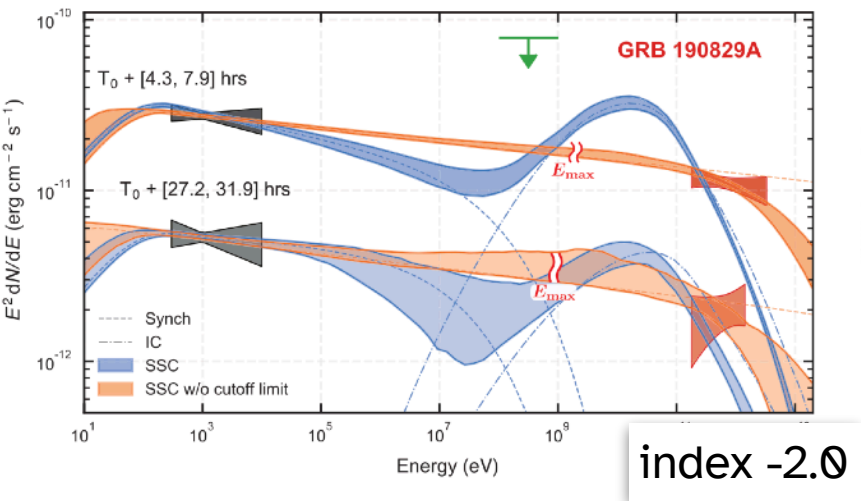
[MAGIC, Nature 575 (2019)]



“yes?”

GRB 190829A

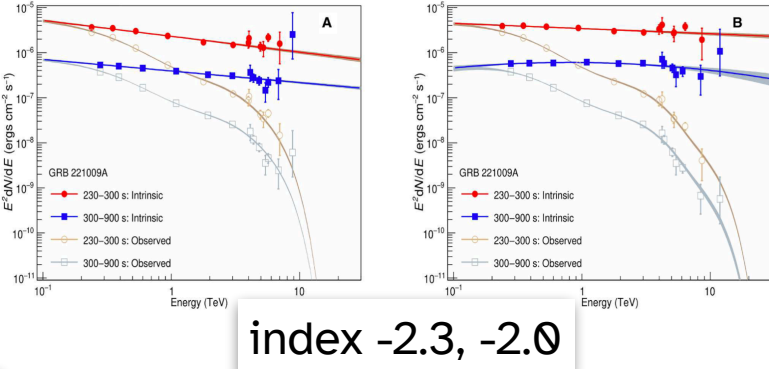
[H.E.S.S. et al., Science 372 (2021)]



“no”

GRB 221009A

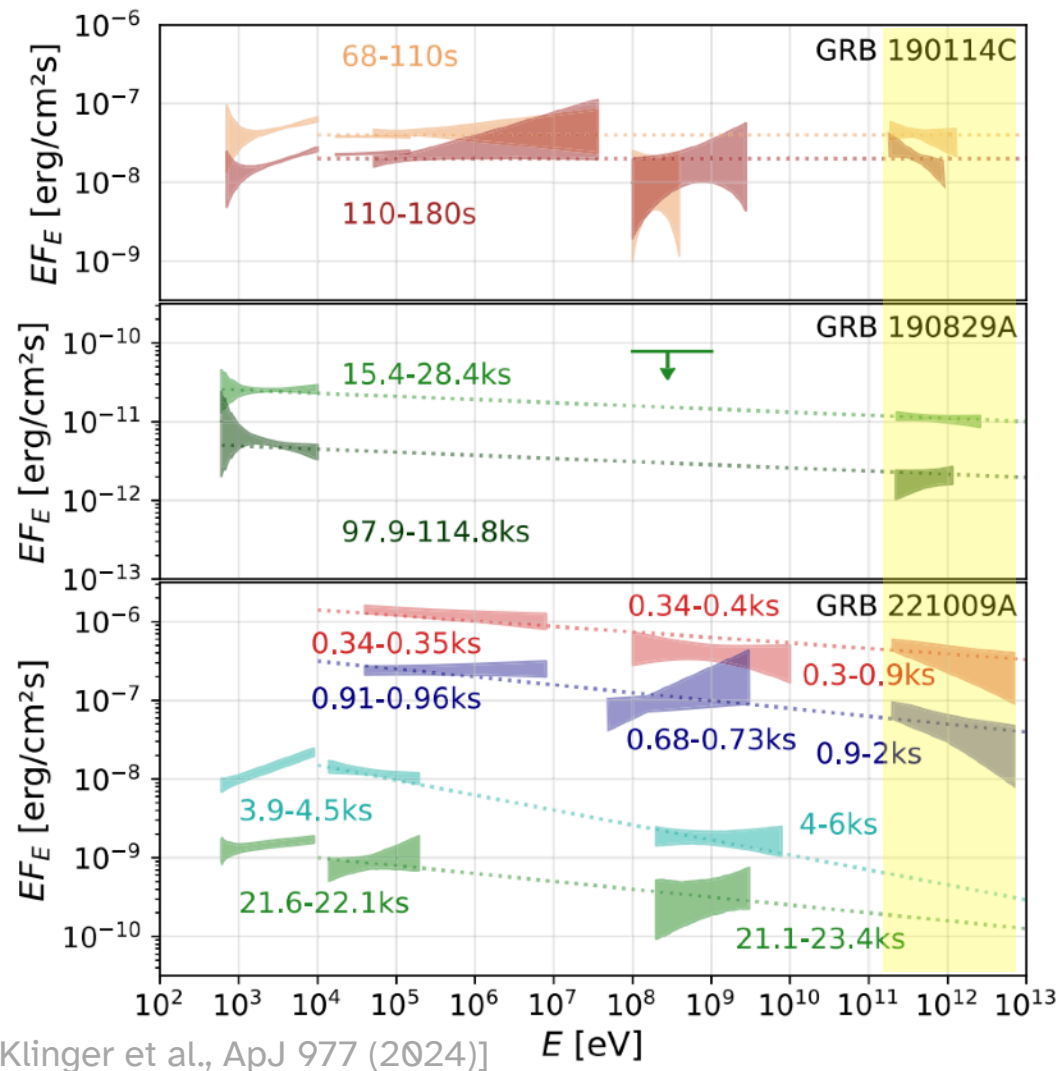
[LHAASO, Science Advances 9 (2023)]



“no”

So, do we see the inverse Compton component in VHE GRBs?

The three best test cases (imo)

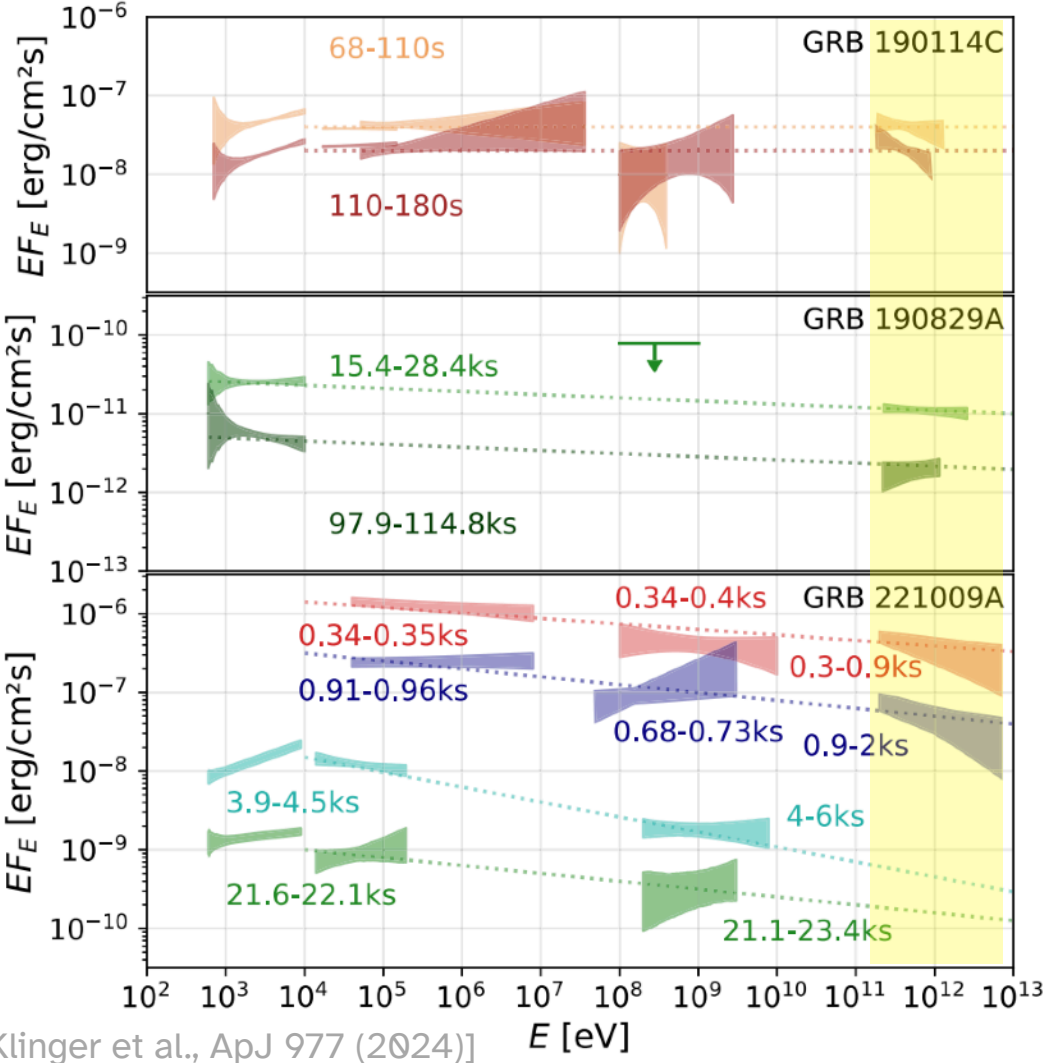


There is no smoking gun so far

[M. Klinger et al., ApJ 977 (2024)]

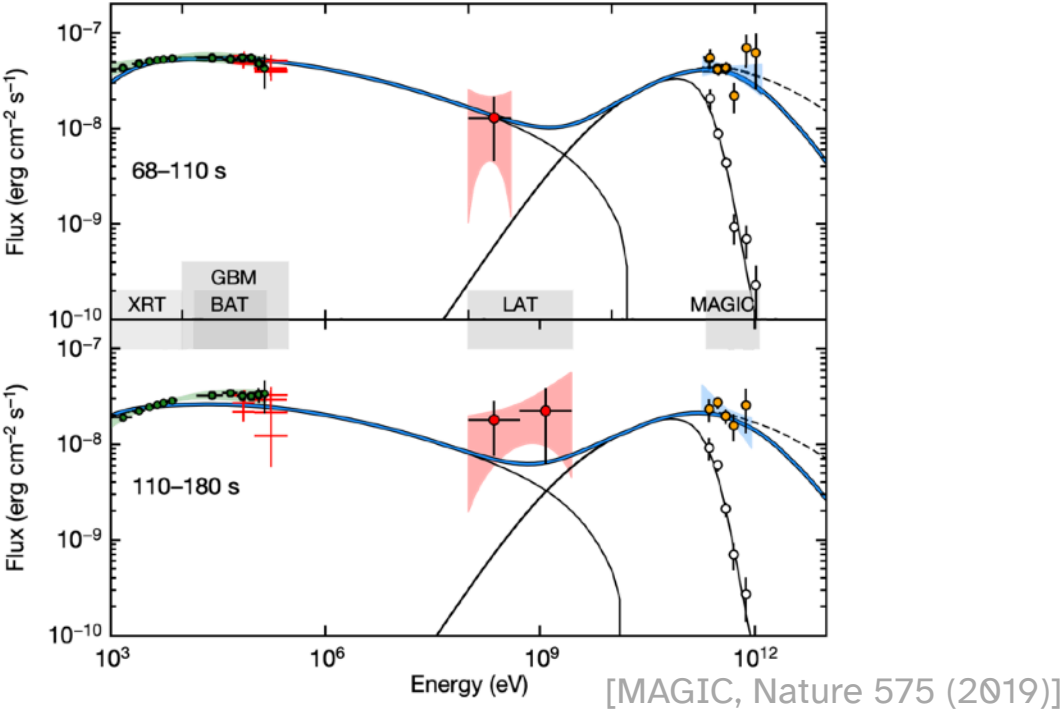
So, do we see the inverse Compton component in VHE GRBs?

The three best test cases (imo)



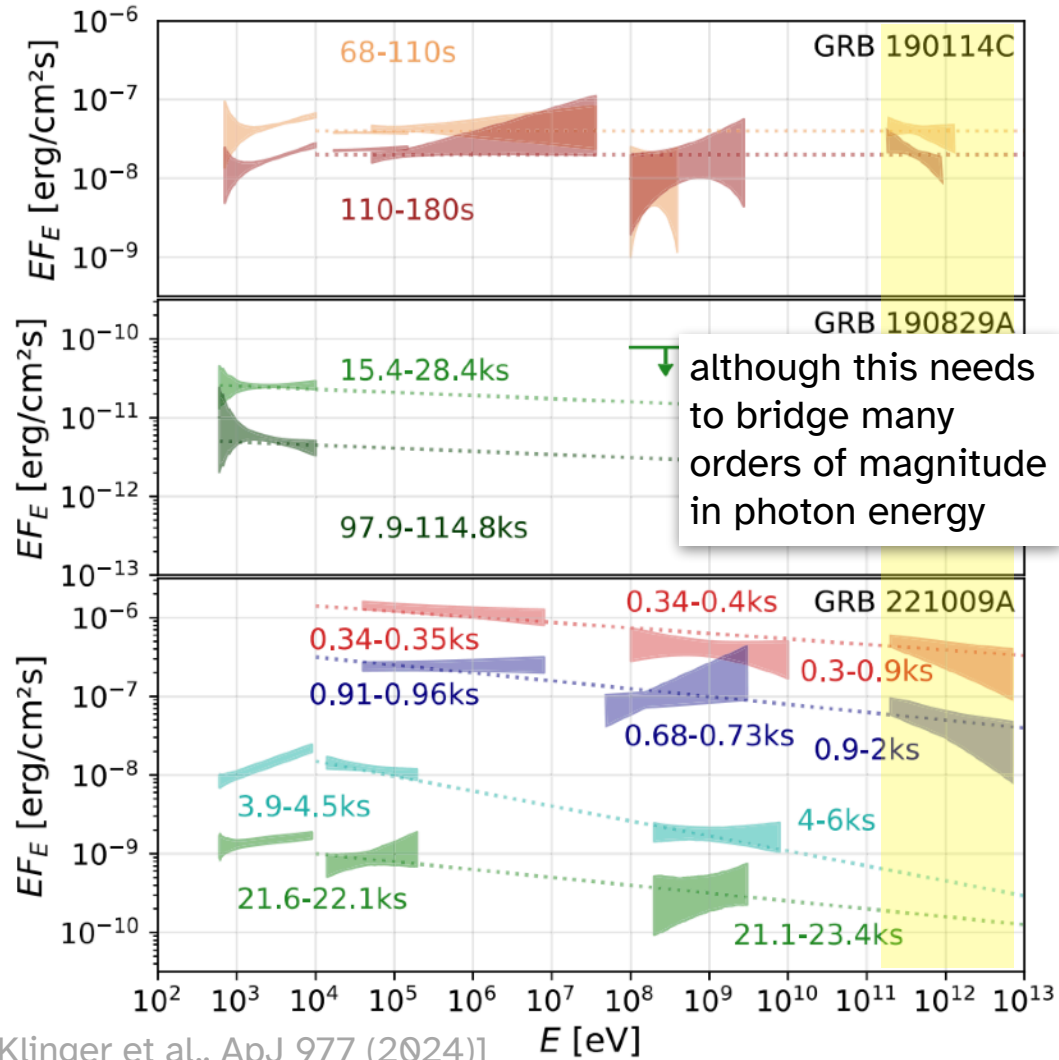
There is no smoking gun so far

Although others disagree:



So, do we see the inverse Compton component in VHE GRBs?

The three best test cases (imo)

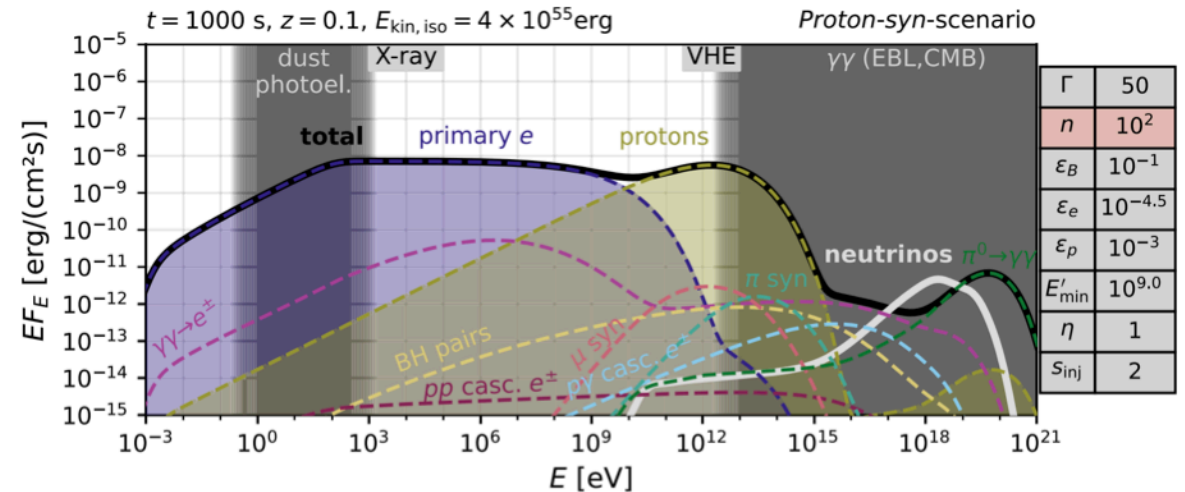


although this needs to bridge many orders of magnitude in photon energy

How do we get flat spectra across such a wide energy range?

Possibilities:

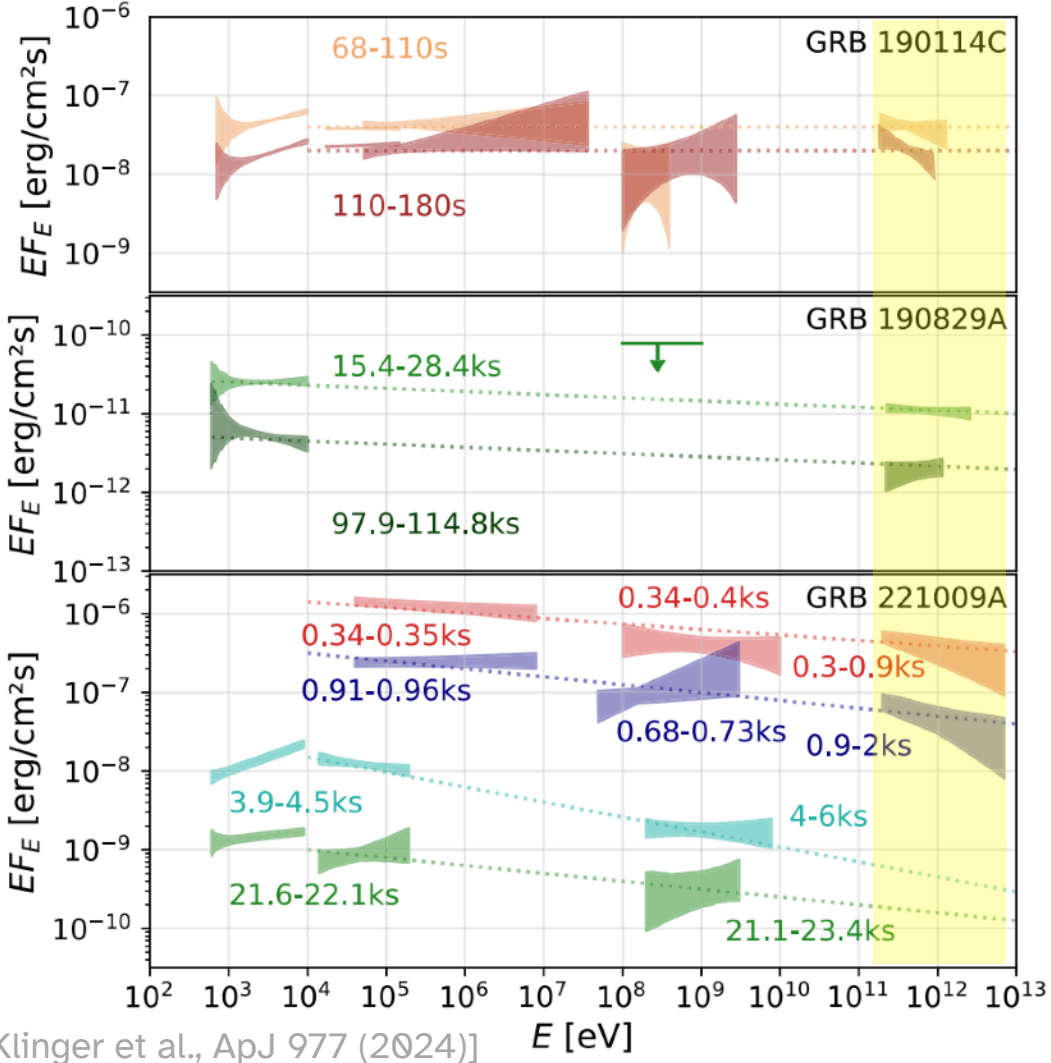
- structure in the magnetic field (multi-zone)
- exploring more complex single-zone scenarios



[M. Klinger et al., ApJ 977 (2024)]

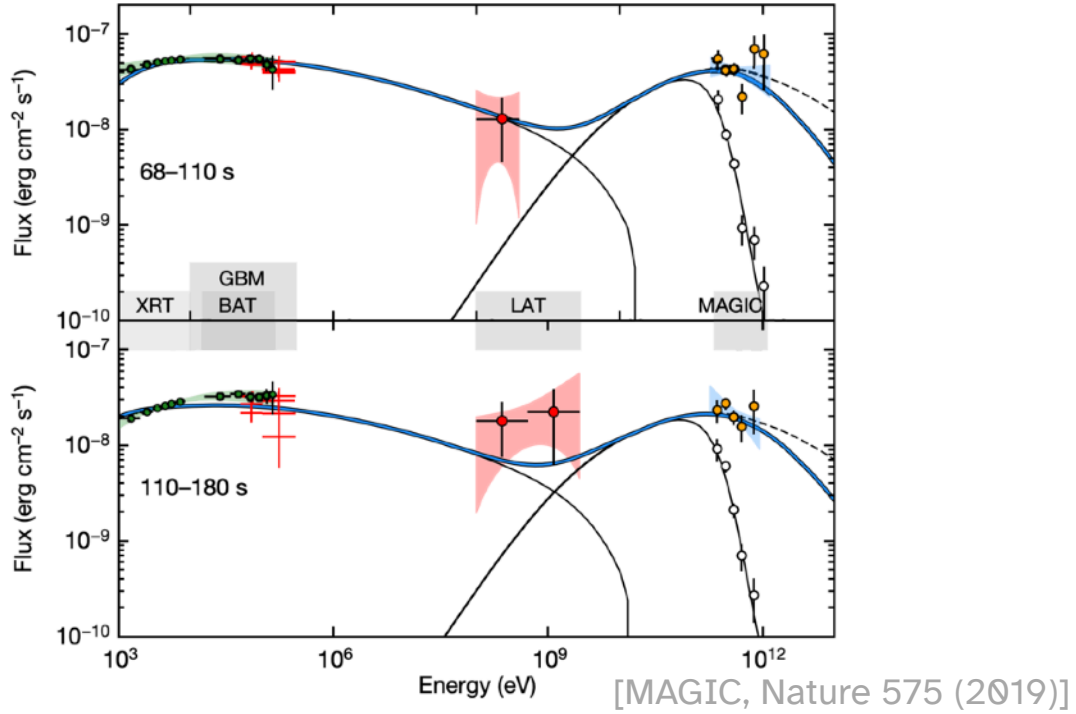
So, do we see the inverse Compton component in VHE GRBs?

The three best test cases (imo)



There is no smoking gun so far

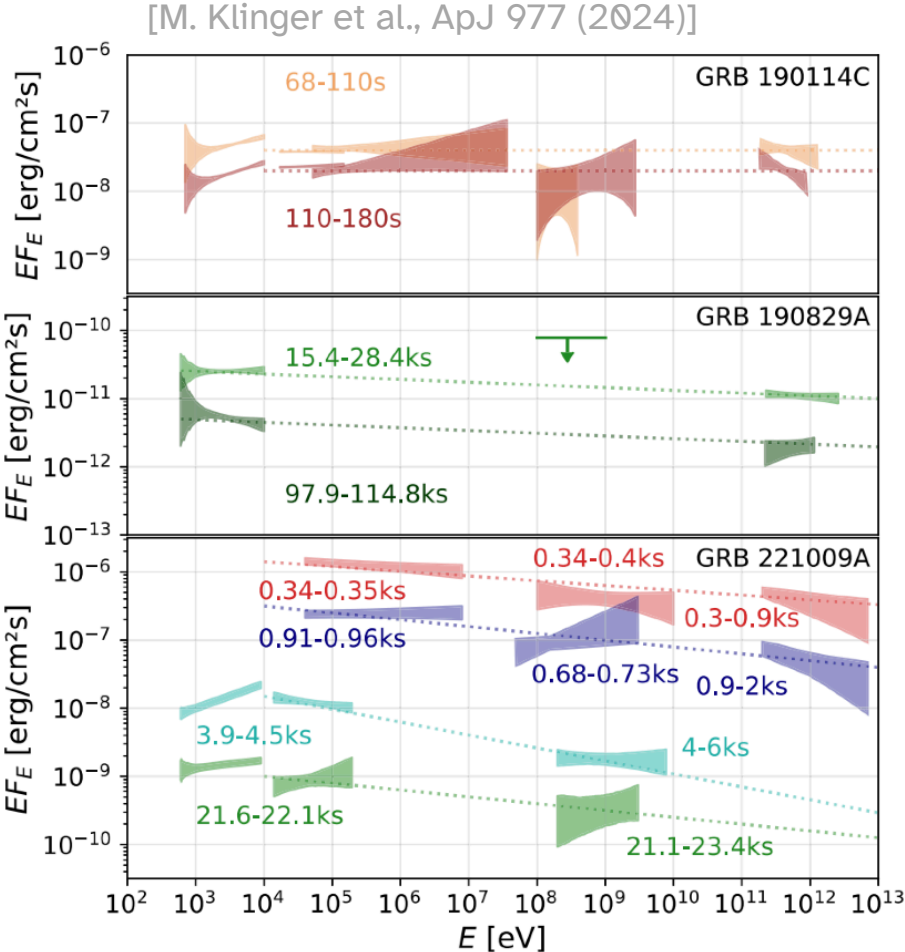
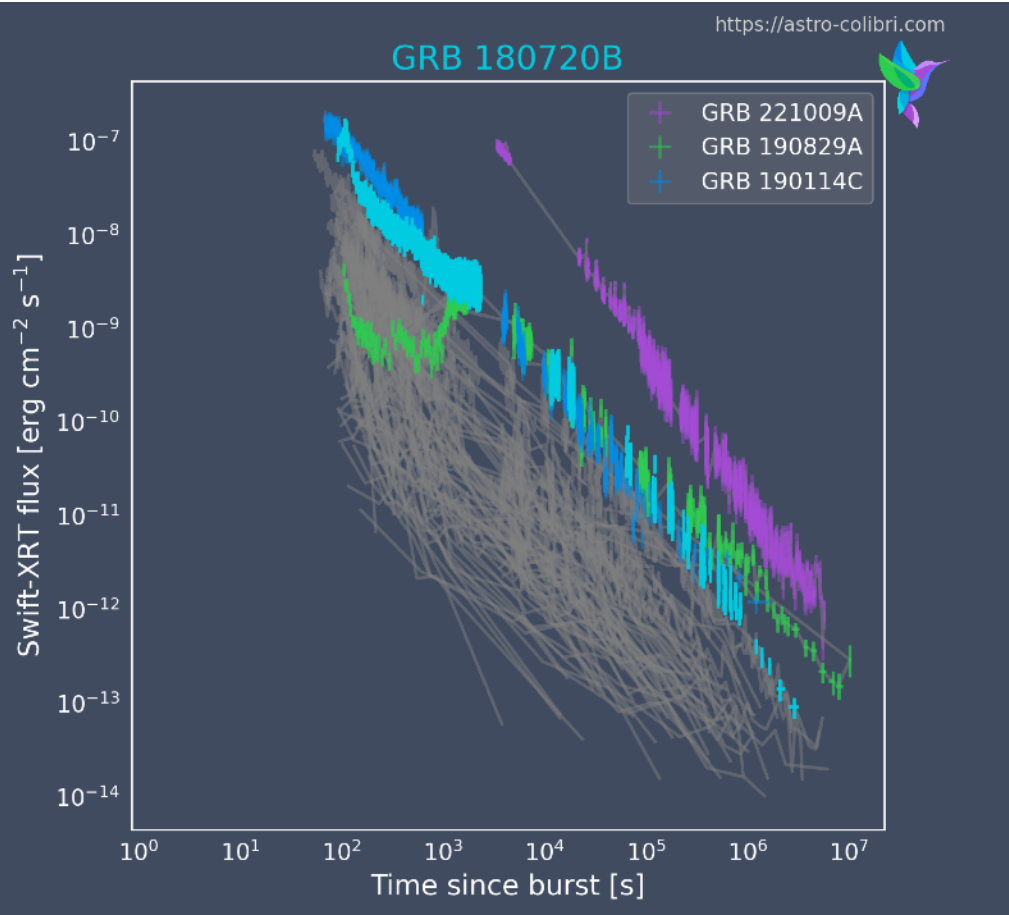
Although others disagree:



Gamma-ray bursts

Prospects for CTAO?

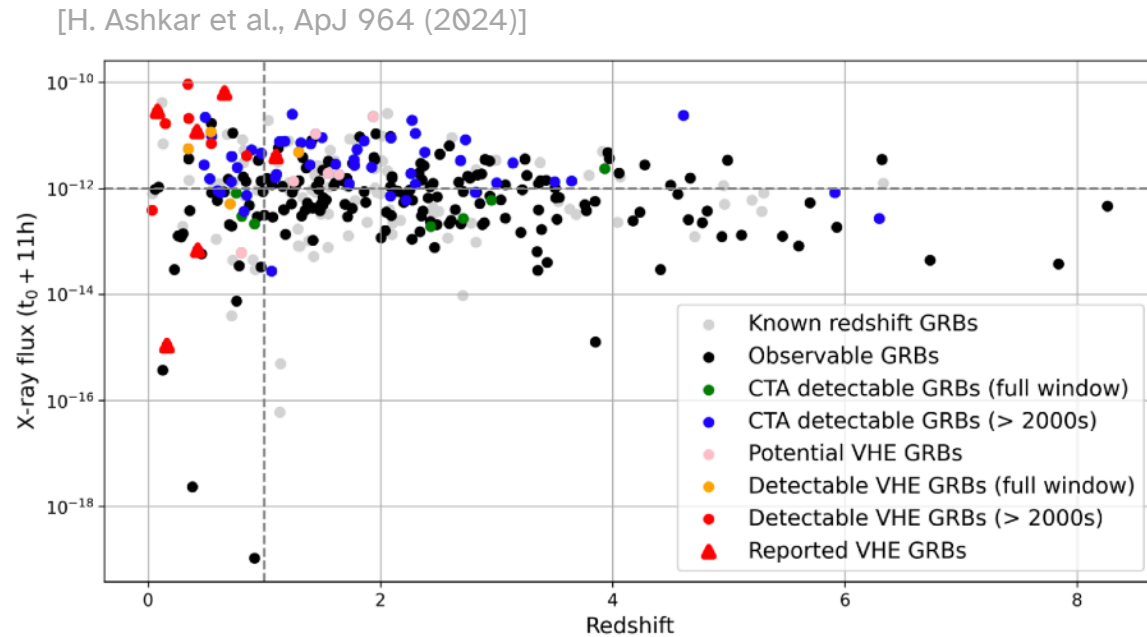
VHE GRBs seem to be X-ray bright (this is at least partly because of low redshifts, although how much?)



Gamma-ray bursts

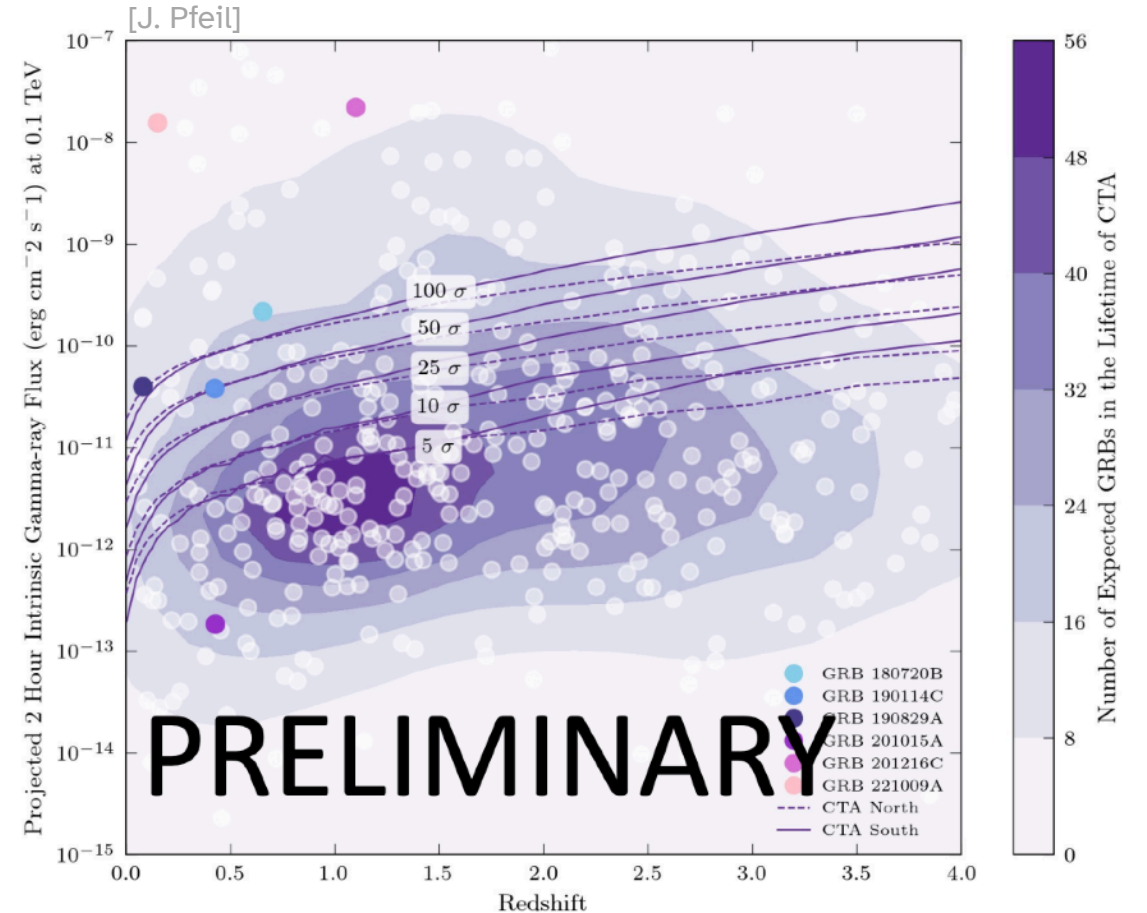
Prospects for CTAO?

Assuming a relation between X-ray and VHE emission, we can predict what would be detectable by CTAO



although:

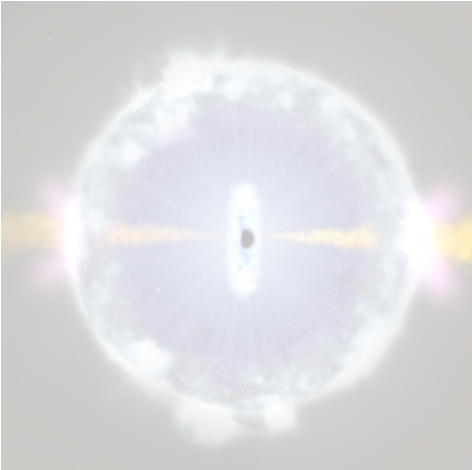
website⁸ (Bernlöhr et al. 2013). We do not aim to establish prospects for CTA. We only show in a qualitative manner what CTA could have done in comparison with current IACTs.



Gamma-ray bursts

What causes them?

[NASA's Goddard Space Flight Center]



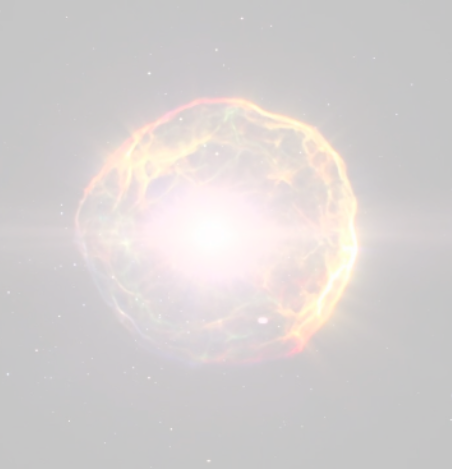
NASA's Goddard Space Flight Center/CI Lab



two neutron stars merge
(probably)

or

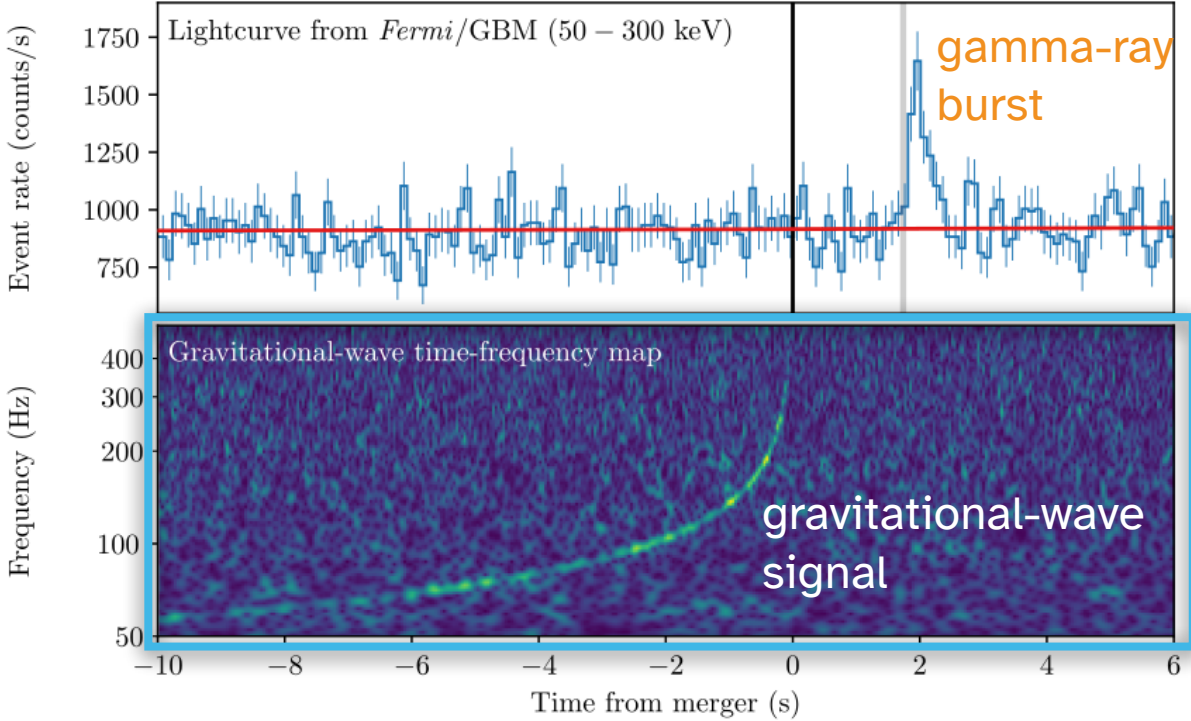
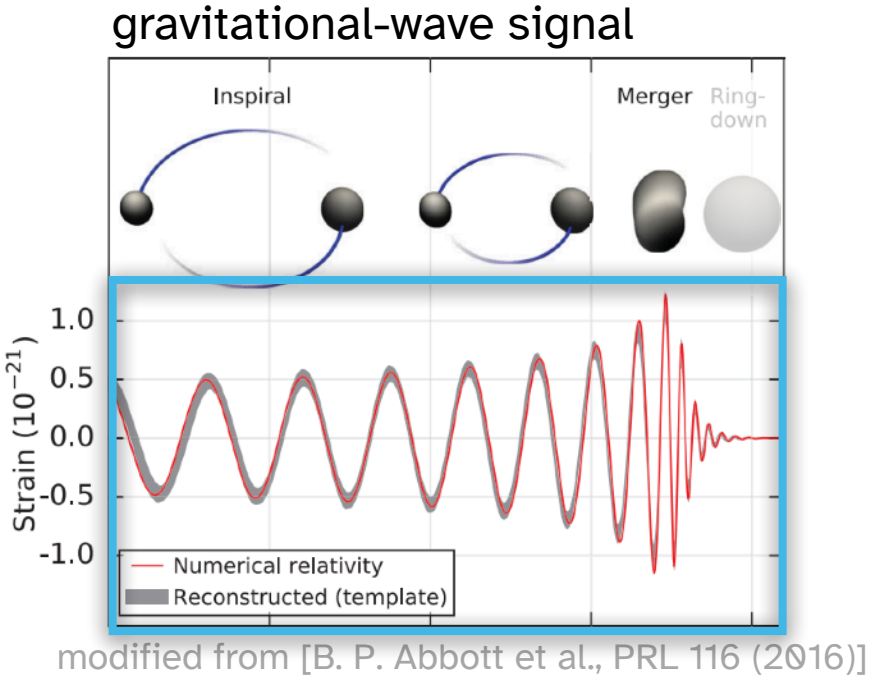
ESO/L Calçada



a massive star collapses

GW170817 + GRB 170817A

The only clear case (so far) of multimessenger detections of a neutron star merger

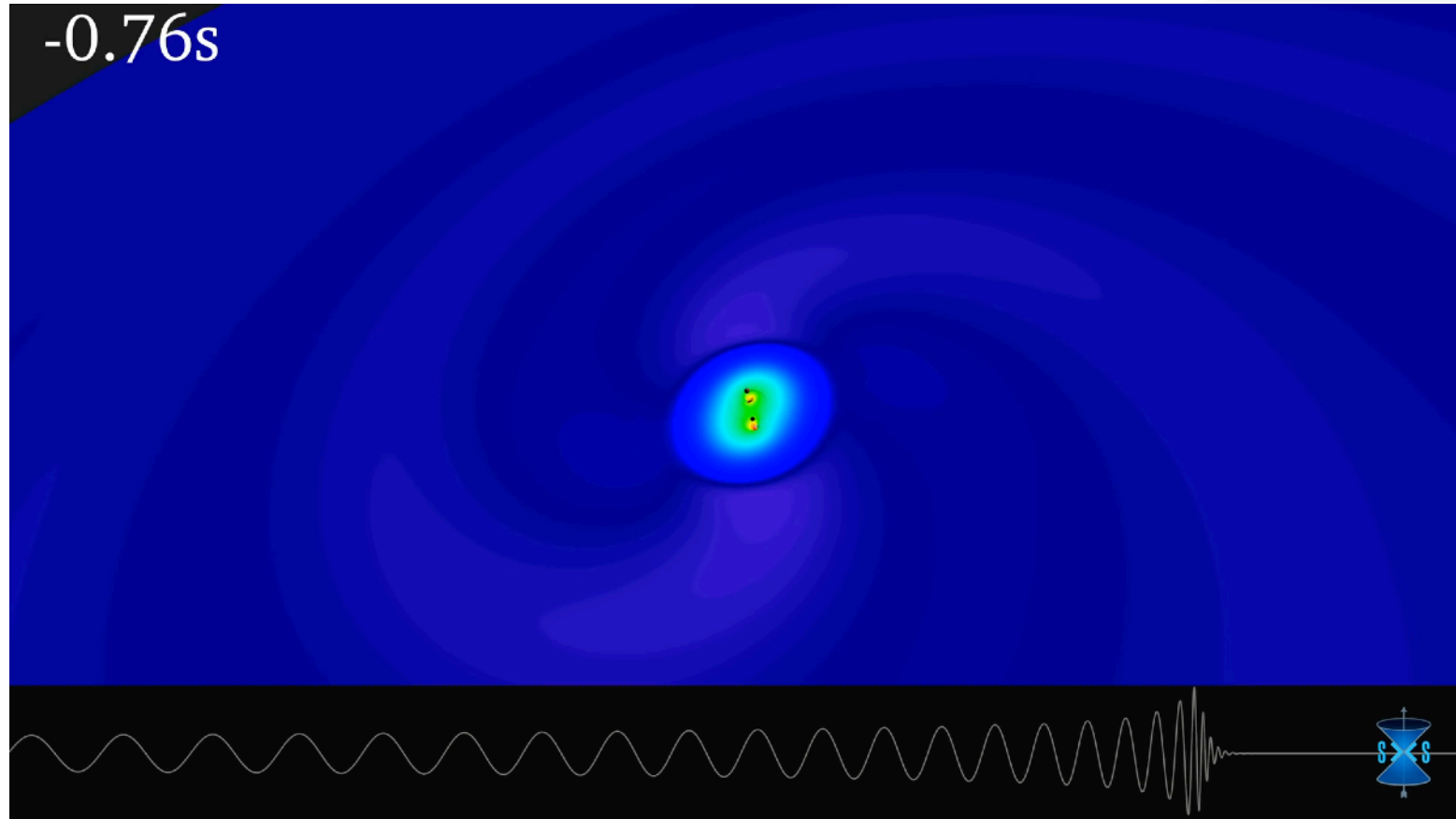


Pause for gravitational waves

How do gravitational-waves interferometers work?

Anything with a changing mass quadrupole moment produces GWs

~ non-axisymmetric and rotating



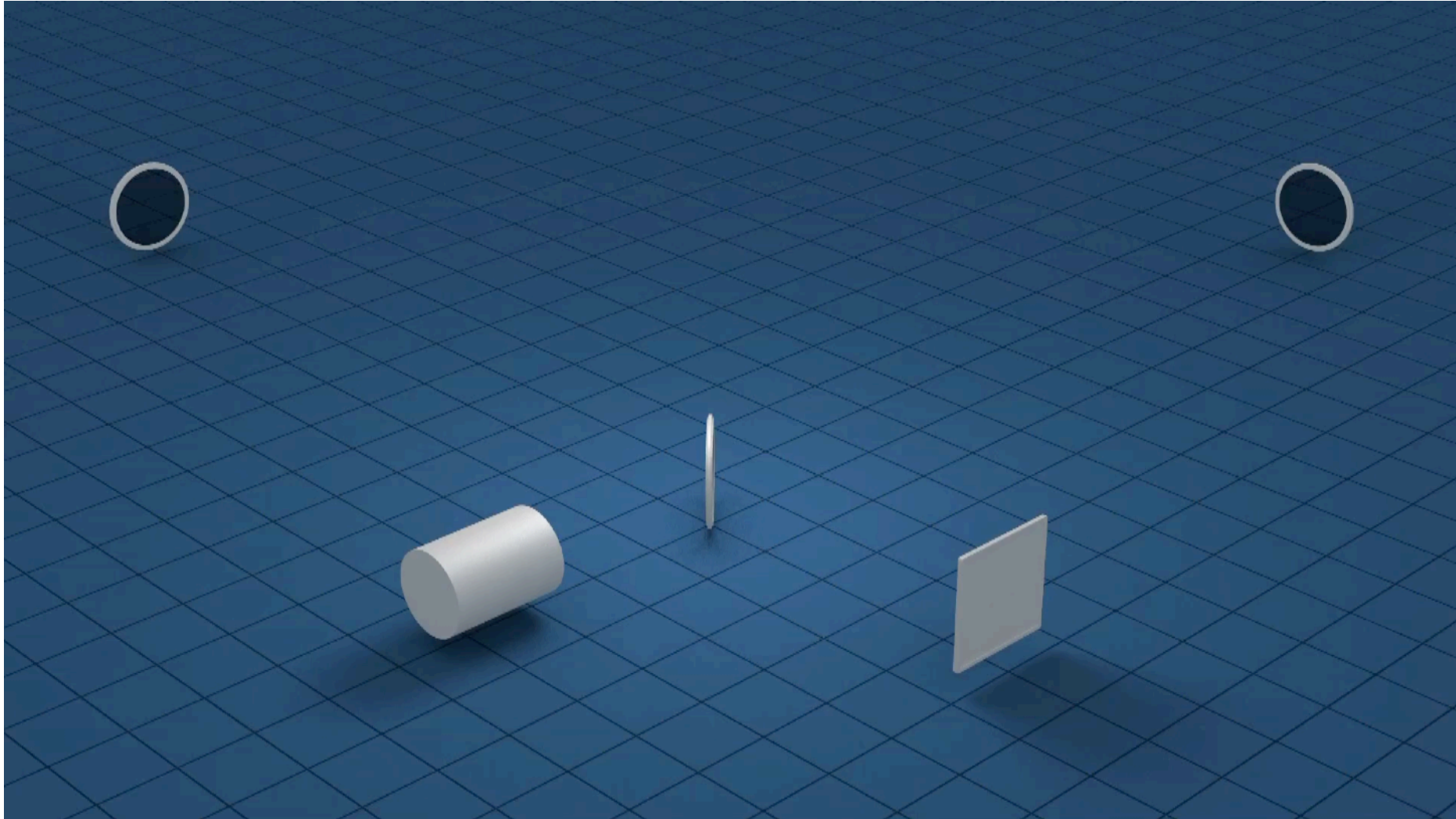
Animation created by SXS, the Simulating eXtreme Spacetimes (SXS) project (<http://www.black-holes.org>)

Video and explanation: <https://www.ligo.caltech.edu/video/ligo20160211v10>

Pause for gravitational waves

How do gravitational-waves interferometers work?

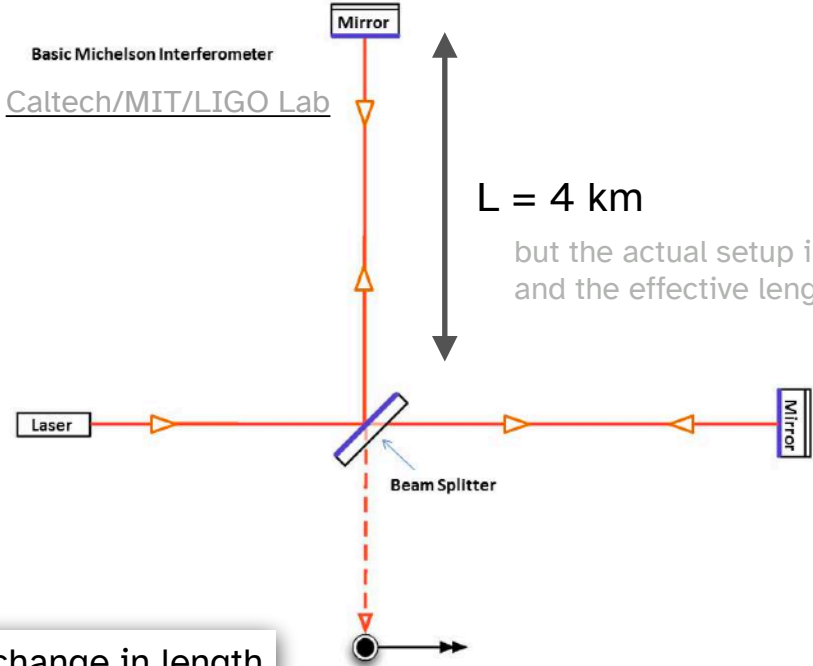
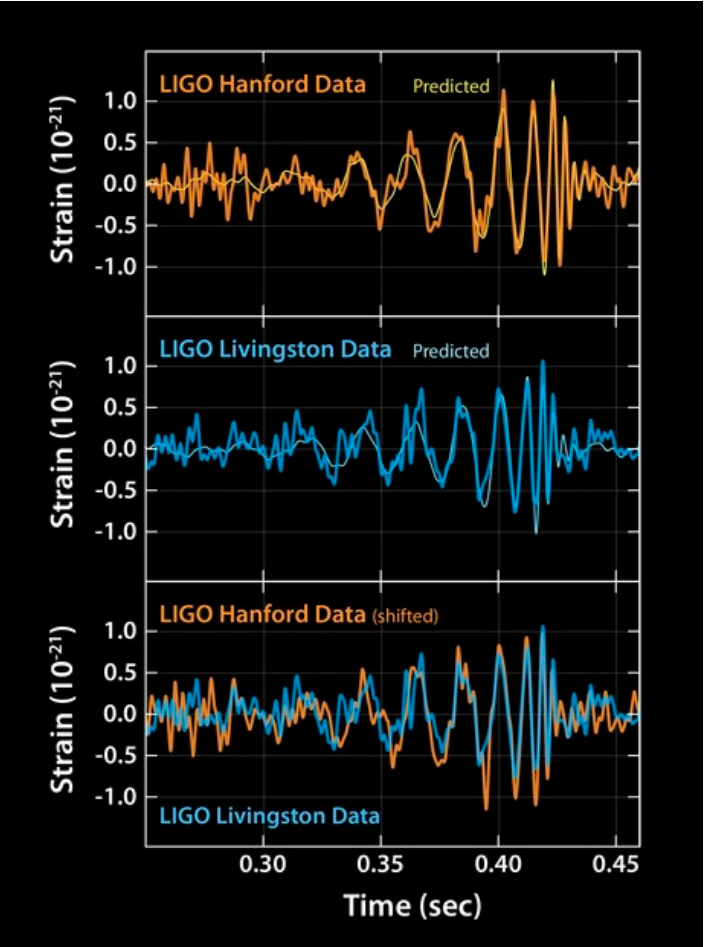
LIGO/T. Pyle



Pause for gravitational waves

How do gravitational-waves interferometers work?

Caltech/MIT/LIGO Lab

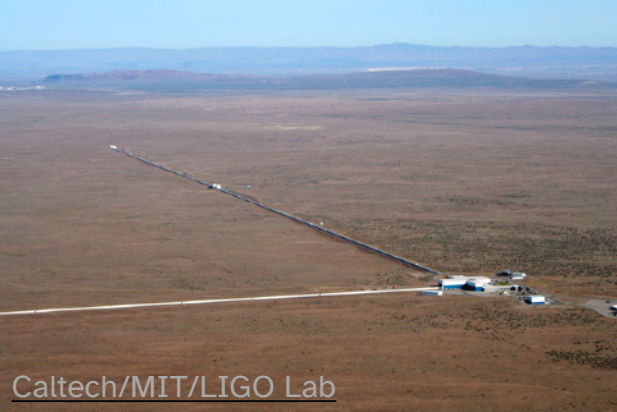


$$h = \frac{\Delta L}{L} = 10^{-21} \quad \text{so} \quad \Delta L \sim 10^{-18} \text{ m}$$

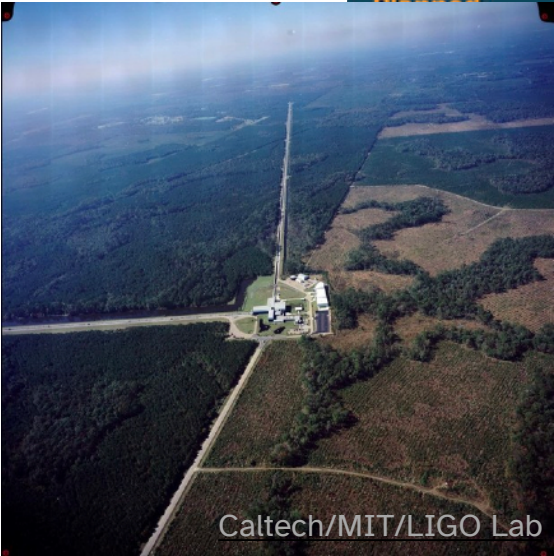
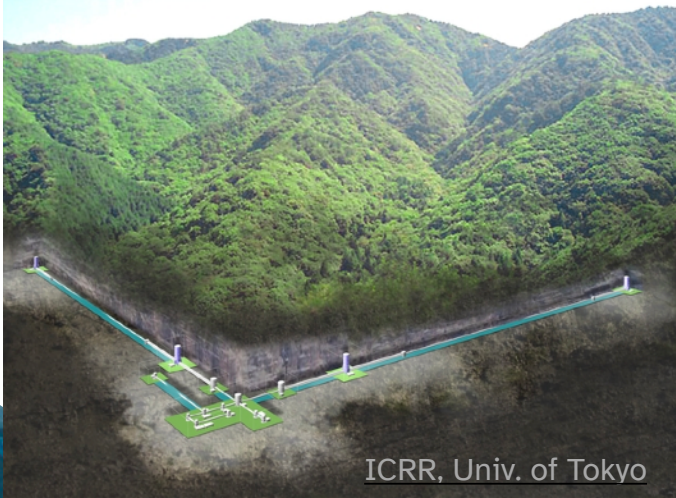
(in comparison, a proton radius is 10^{-15} m)

Pause for gravitational waves

The network of GW interferometers



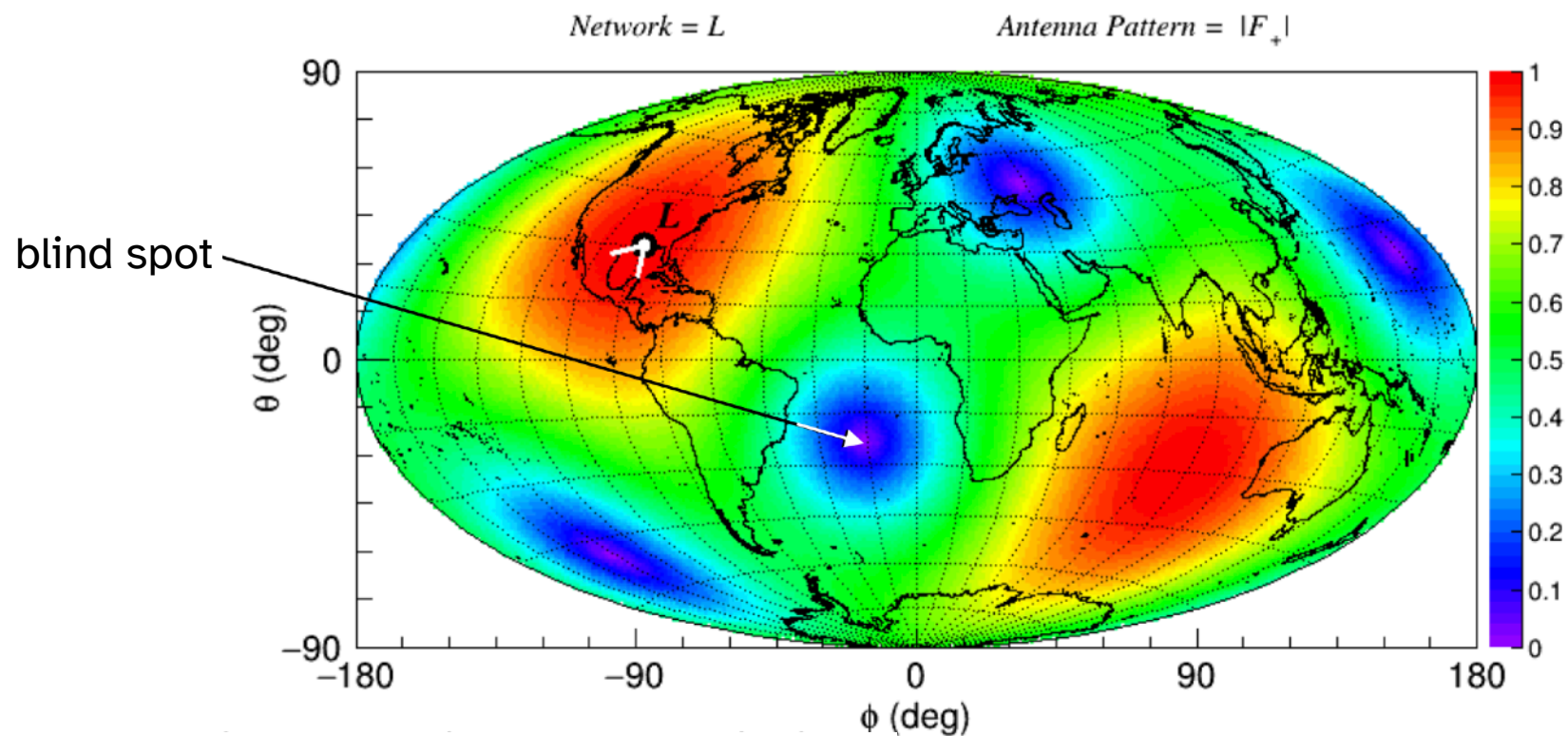
Caltech/MIT/LIGO Lab



Pause for gravitational waves

Why are GW localizations so uncertain?

GW interferometers individually have very poor localization capabilities



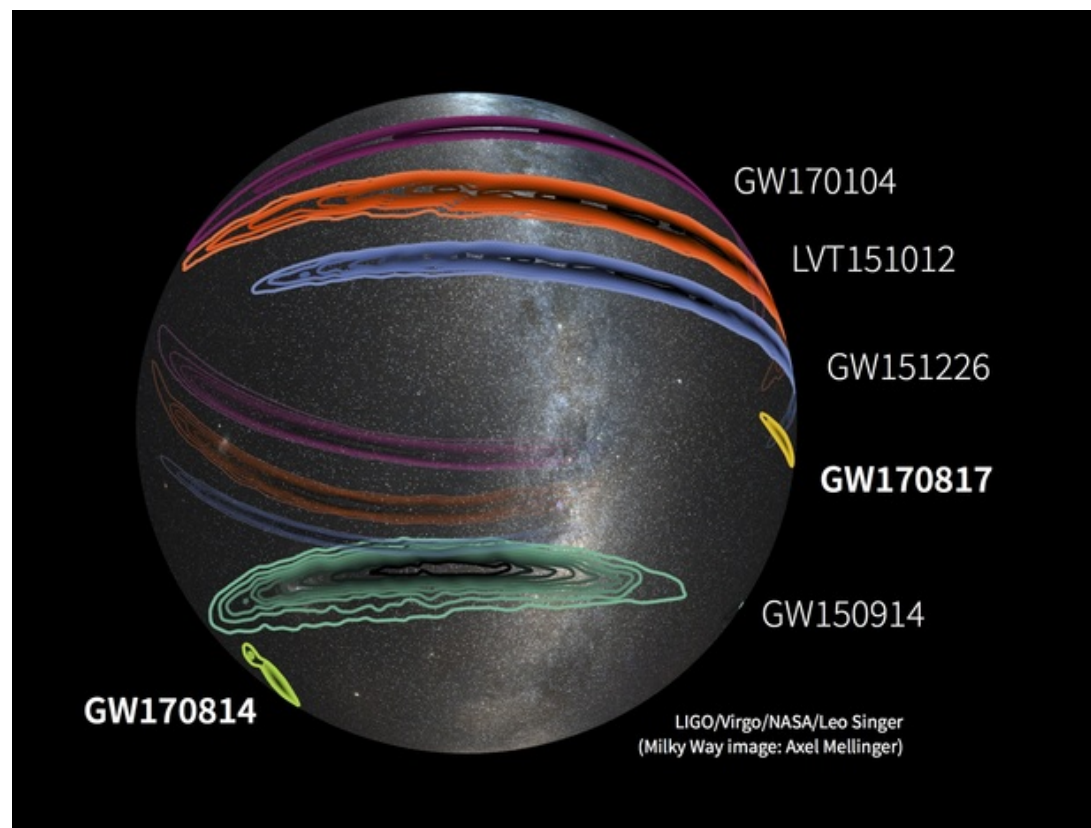
[G. A. Pronti, Otranto School 2021]

Pause for gravitational waves

Why are GW localizations so uncertain?

GW interferometers individually have very poor localization capabilities

Detection by ...	localization is ...
single detector	~all sky
two detectors	bananas
three+ detectors	manageable

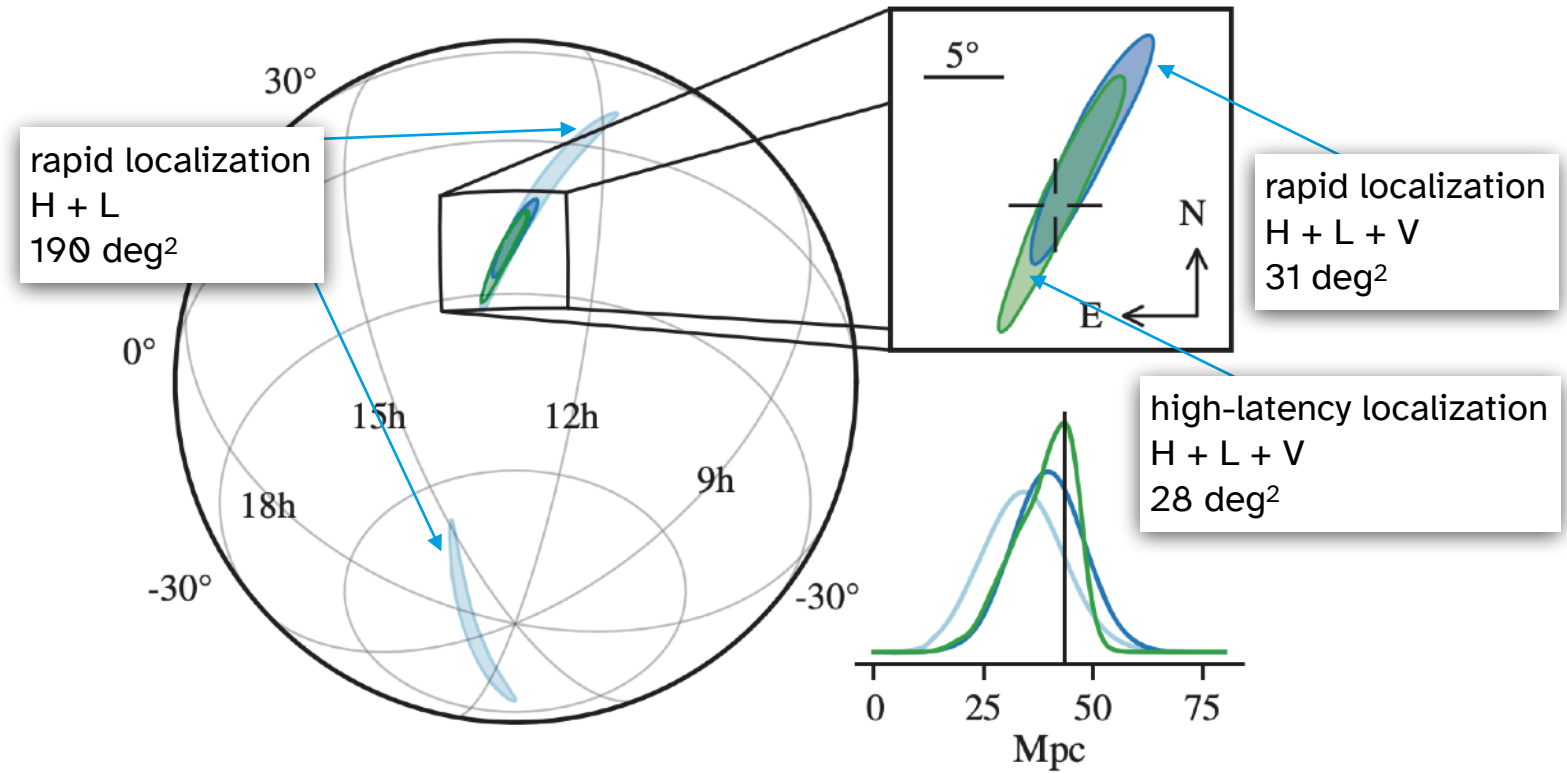
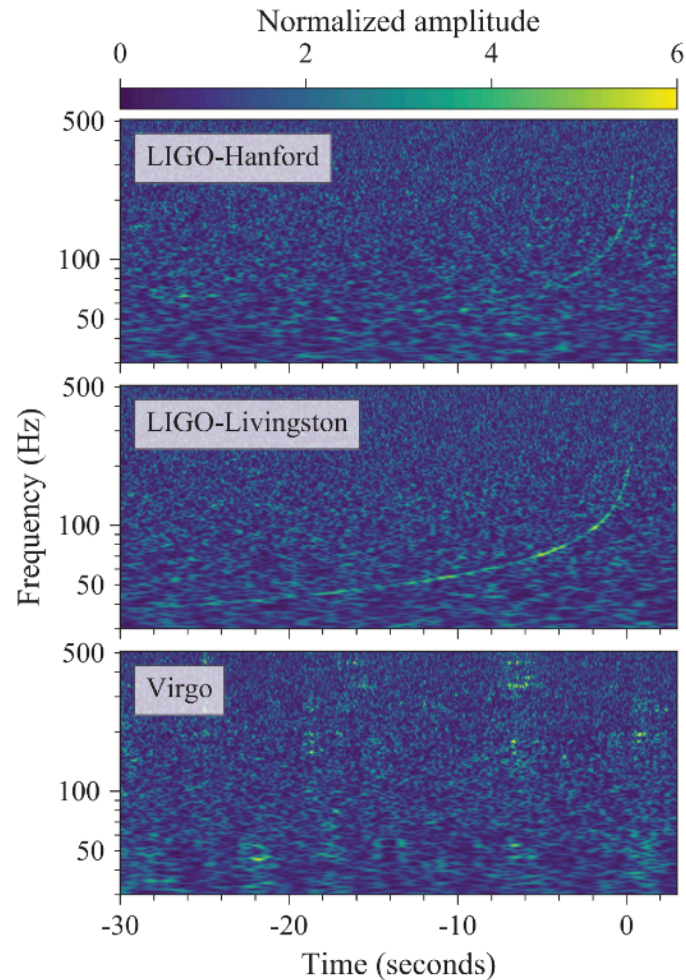


[LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)]

GW170817

GW 170817 was ~detected by three GW interferometers

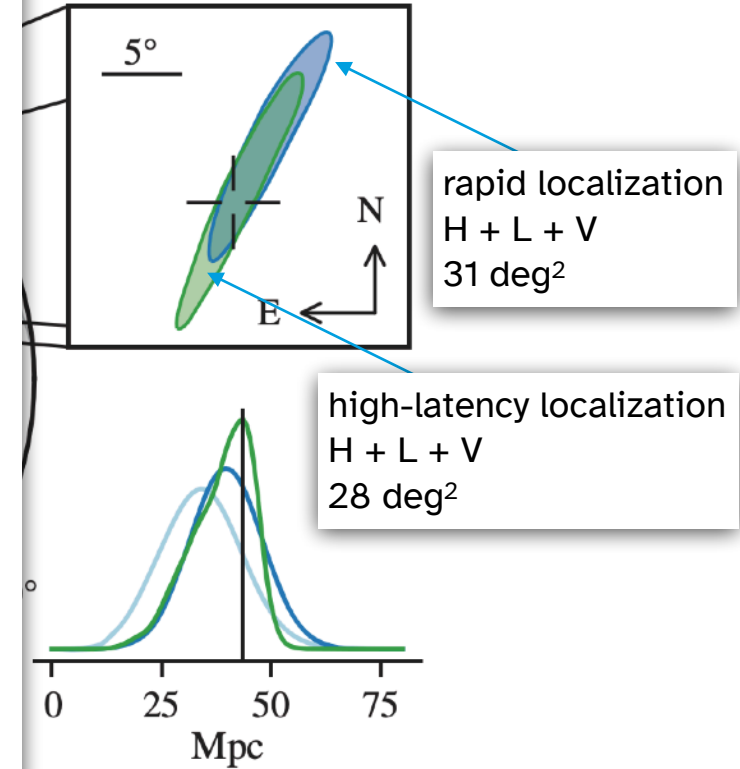
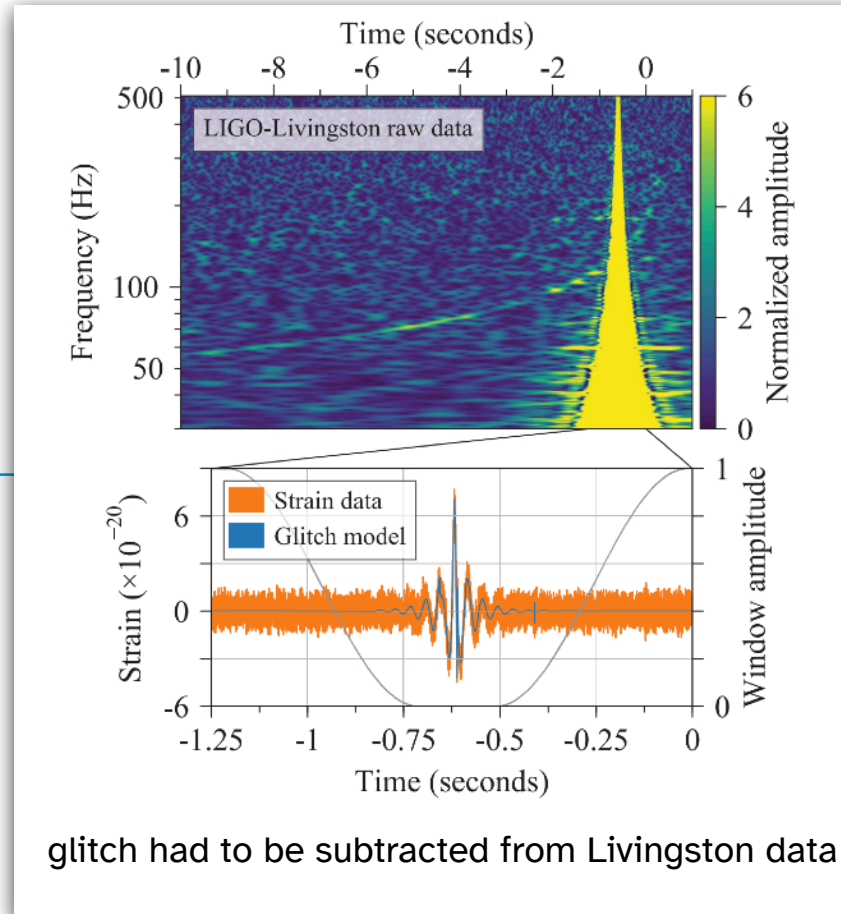
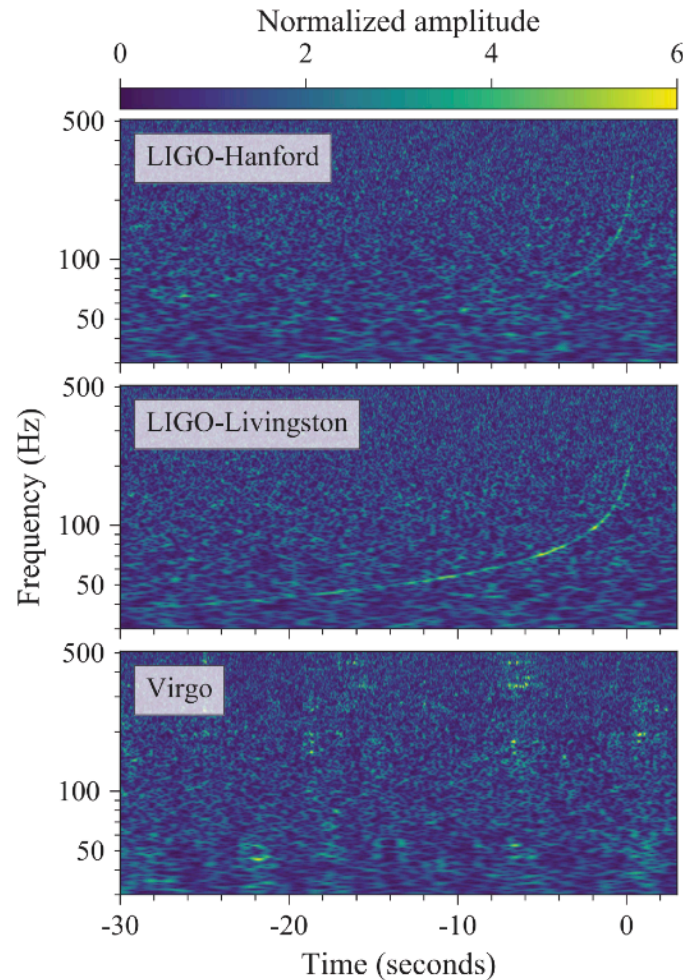
[B. P. Abbott et al., PRL 119 (2017)]



GW170817

GW 170817 was ~detected by three GW interferometers

[B. P. Abbott et al., PRL 119 (2017)]



GW170817 + GRB 170817A

The only clear case (so far) of multimessenger detections of a neutron star merger

[GCNs]

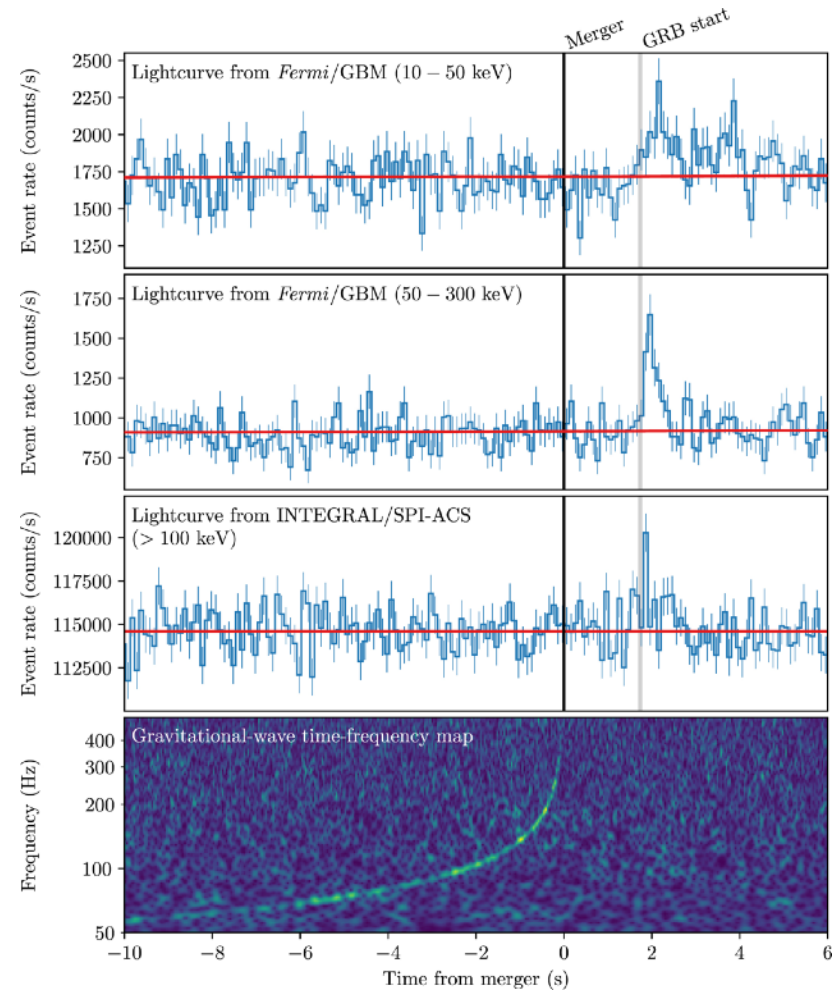
```
////////////////////////////////////  
TITLE:   GCN CIRCULAR  
NUMBER:  21505  
SUBJECT: LIGO/Virgo G298048: Fermi GBM trigger 524666471/170817529: LIGO/Virgo  
          Identification of a possible gravitational-wave counterpart  
DATE:    17/08/17 13:21:42 GMT  
FROM:    Reed Clasey Essick at MIT <ressick@mit.edu>
```

The LIGO Scientific Collaboration and the Virgo Collaboration report:

The online CBC pipeline (gstlal) has made a preliminary identification of a GW candidate associated with the time of Fermi GBM trigger 524666471/170817529 at gps time 1187008884.47 (Thu Aug 17 12:41:06 GMT 2017) with RA=186.62deg Dec=-48.84deg and an error radius of 17.45deg.

The candidate is consistent with a neutron star binary coalescence with False Alarm Rate of $\sim 1/10,000$ years.

An offline analysis is ongoing. Any significant updates will be provided by a new Circular.

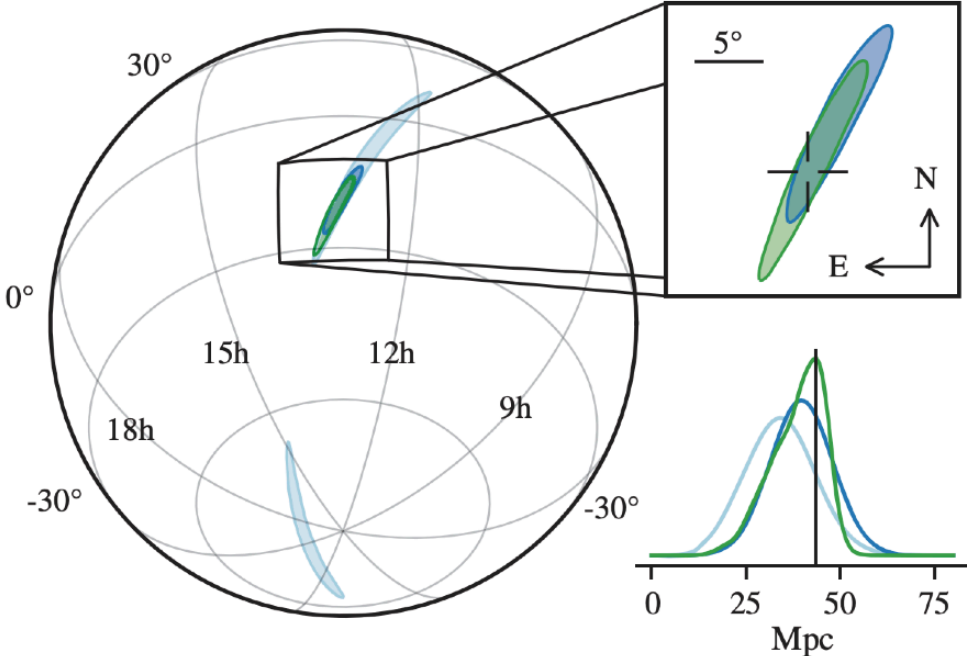


[B. P. Abbott et al., ApJL 848 (2017)]

GW170817 localization

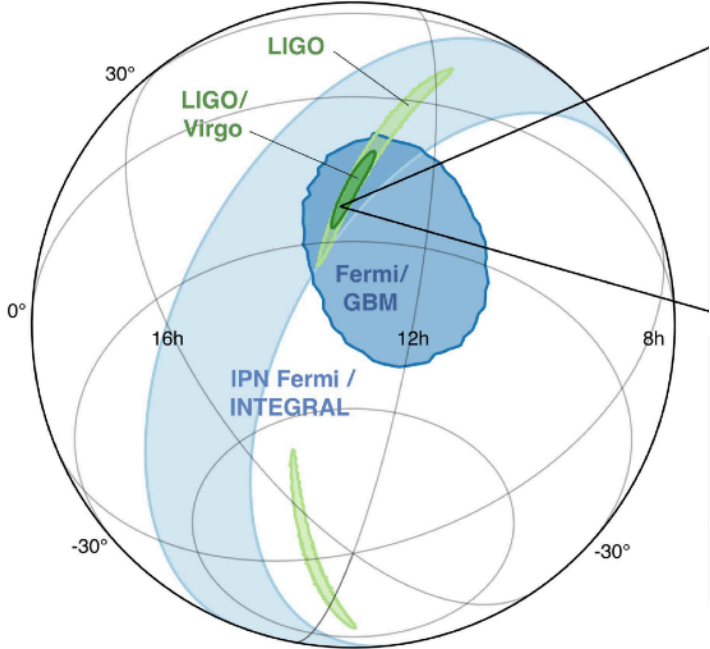
Adding the electromagnetic detections

GW-only localization



[B. P. Abbott et al., PRL 119 (2017)]

GW+GRB localization

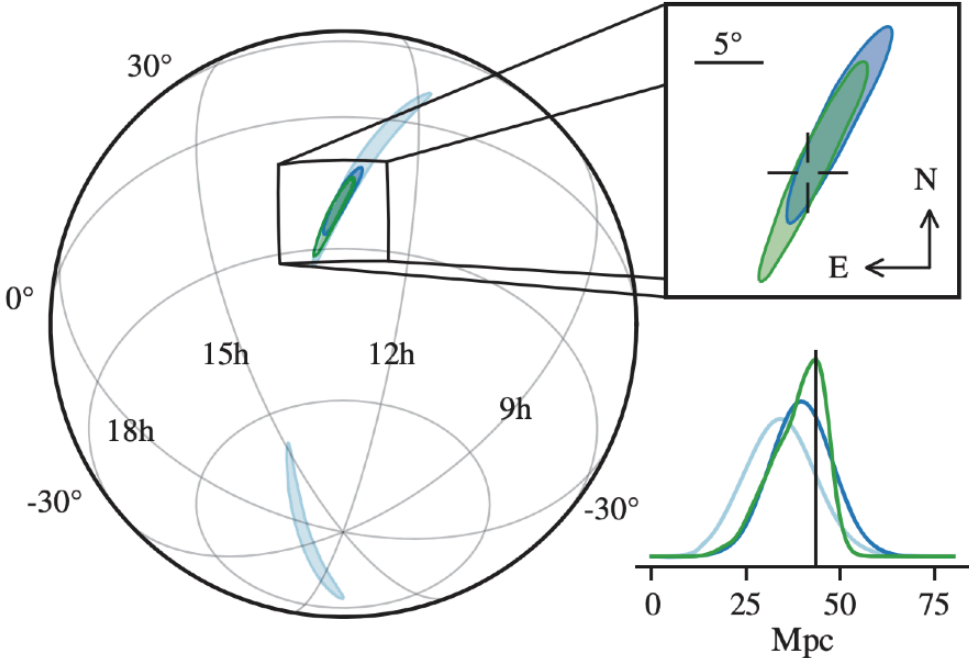


[B. P. Abbott et al., ApJL 848 (2017)]

GW170817 localization

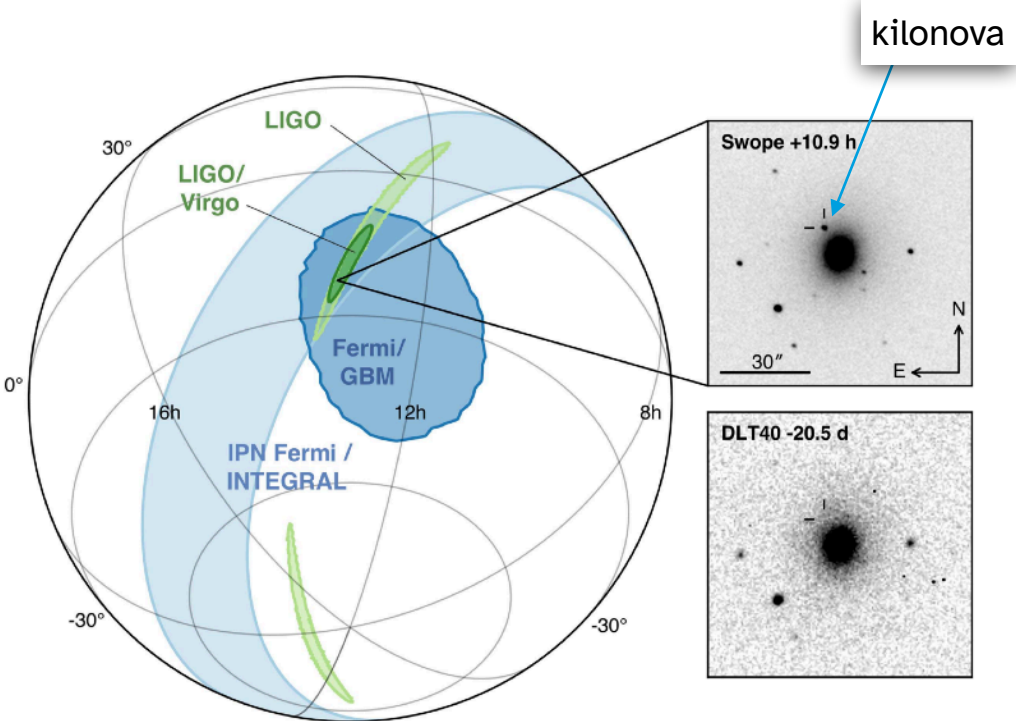
Adding the electromagnetic detections

GW-only localization



[B. P. Abbott et al., PRL 119 (2017)]

GW+GRB localization

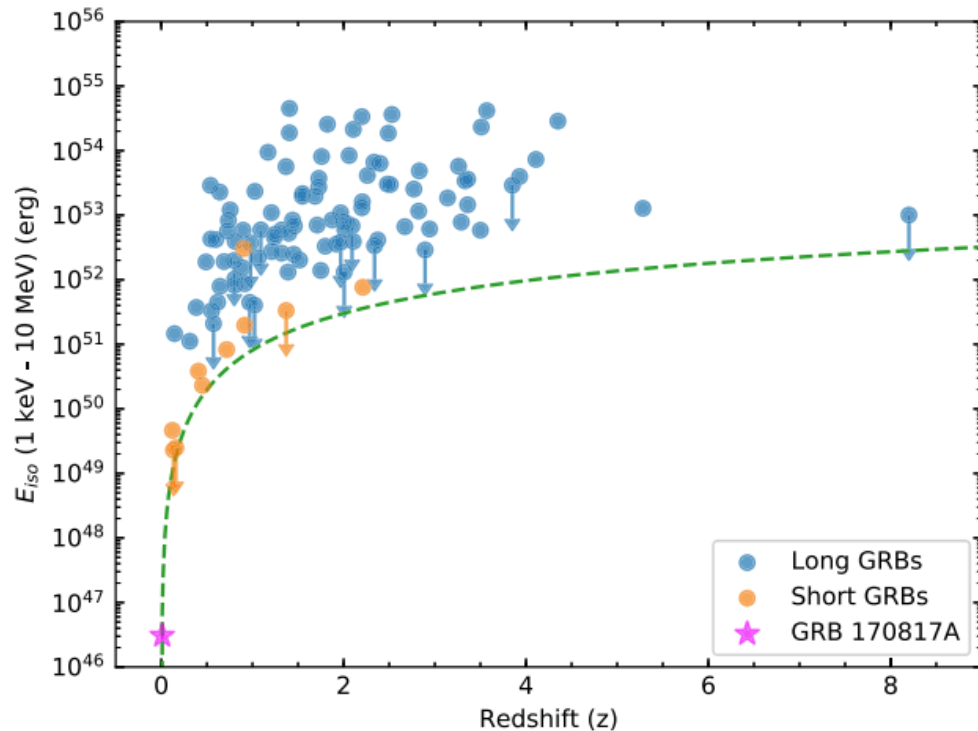


[B. P. Abbott et al., ApJL 848 (2017)]

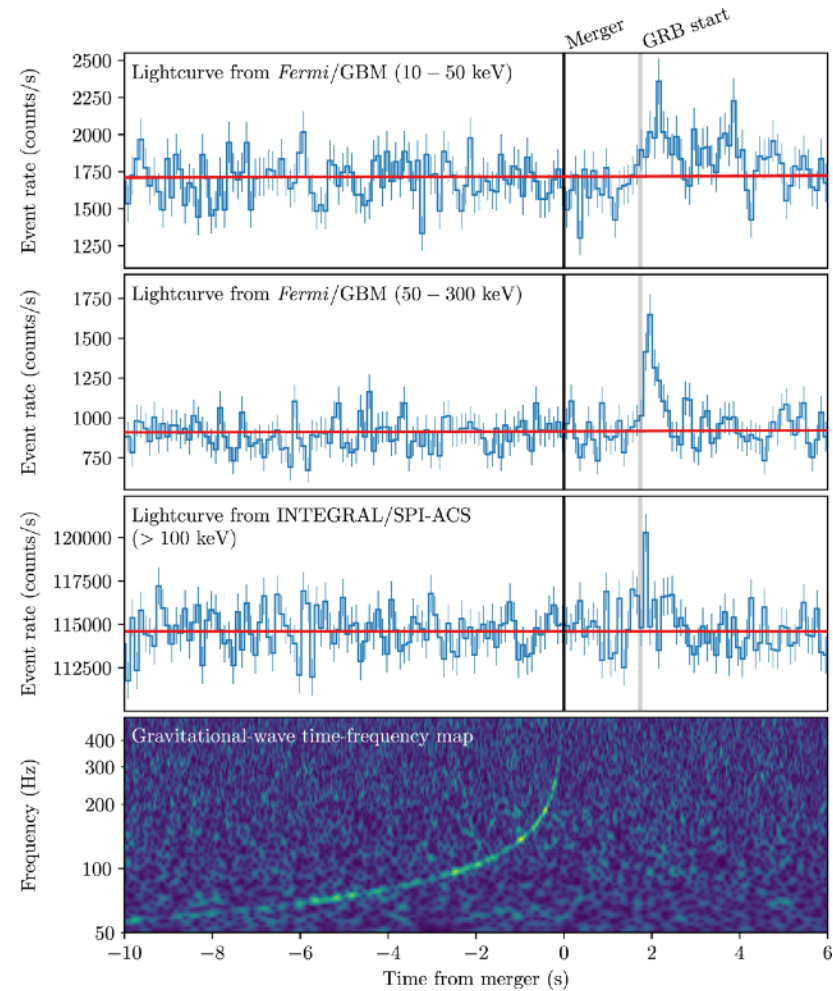
GW170817 + GRB 170817A

The only clear case (so far) of multimessenger detections of a neutron star merger

Very close, but very small energy output?



[B. P. Abbott et al., ApJL 848 (2017)]

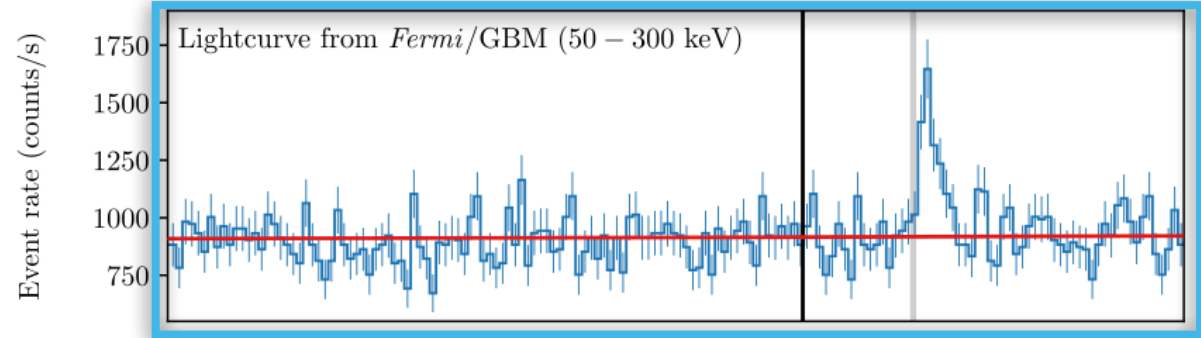
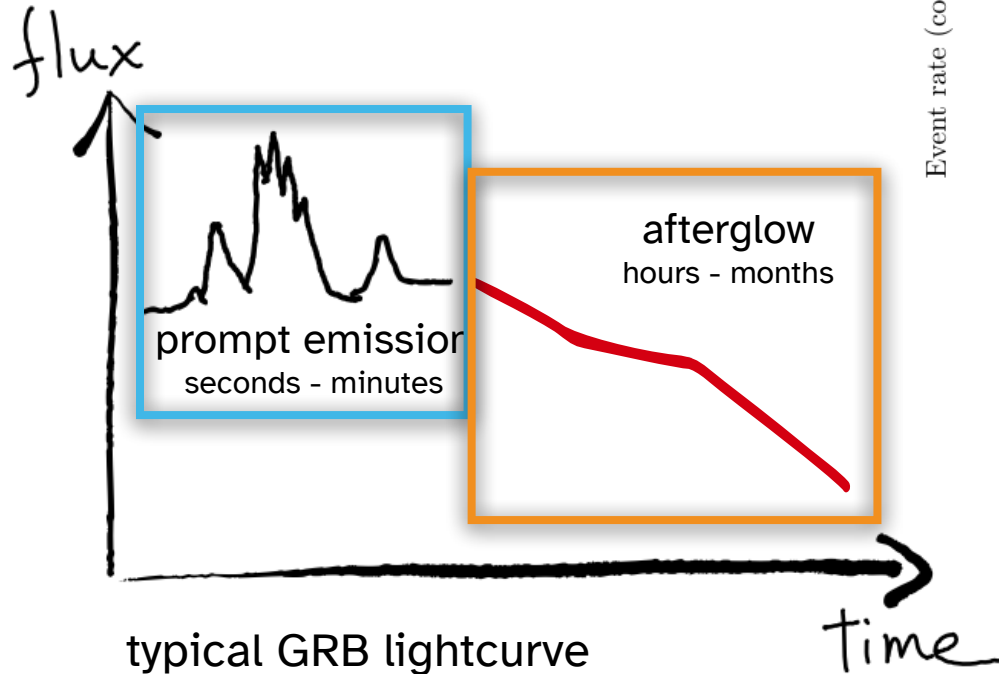


[B. P. Abbott et al., ApJL 848 (2017)]

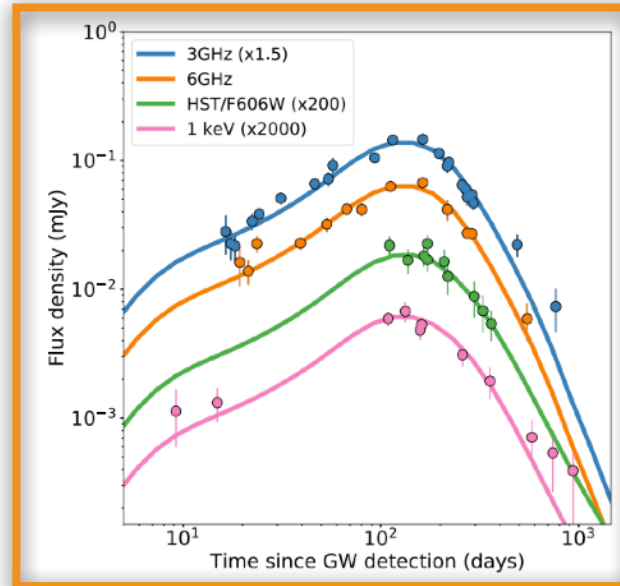
GW170817 + GRB 170817A

The only clear case (so far) of multimessenger detections of a neutron star merger

The lightcurves were odd when compared to the rest of the GRB population



[B. P. Abbott et al., *ApJL* 848 (2017)]



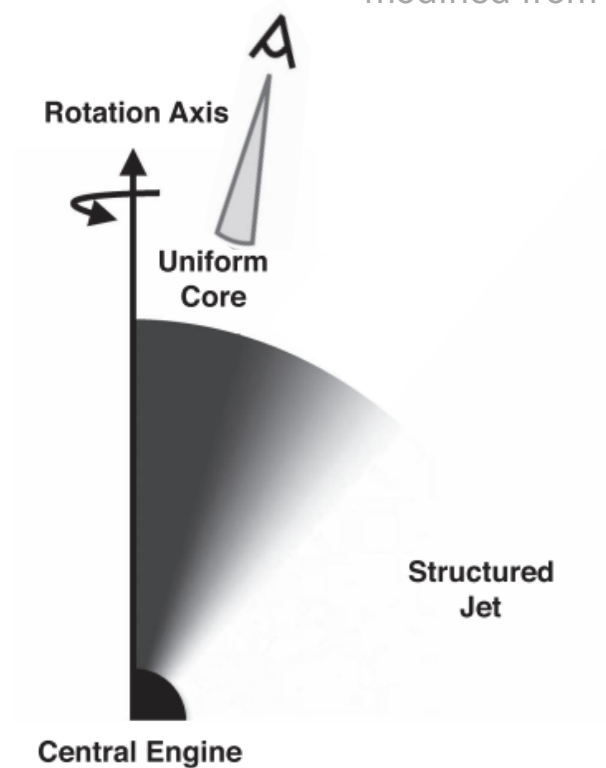
[S. Makhathini et al., *ApJ* 922 (2021)]

GW170817 + GRB 170817A

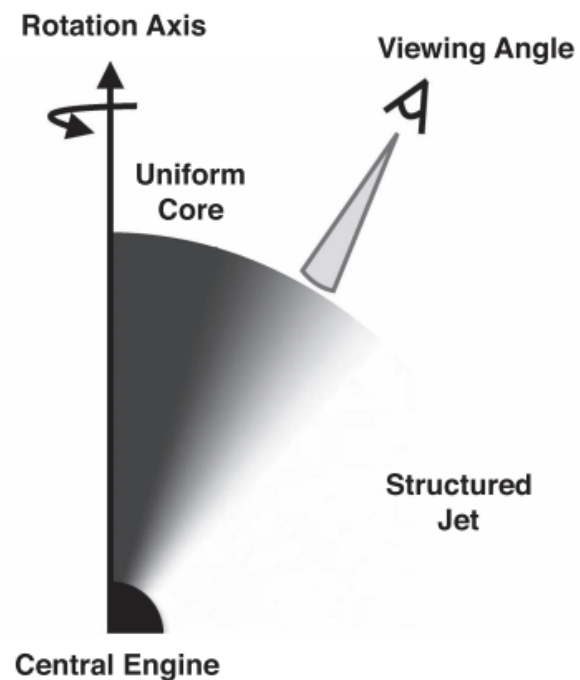
an off-axis GRB

Explanation: We were observing a GRB from outside of the (core of the) jet

modified from [B. P. Abbott et al., ApJL 848 (2017)]



most GRBs are observed on-axis

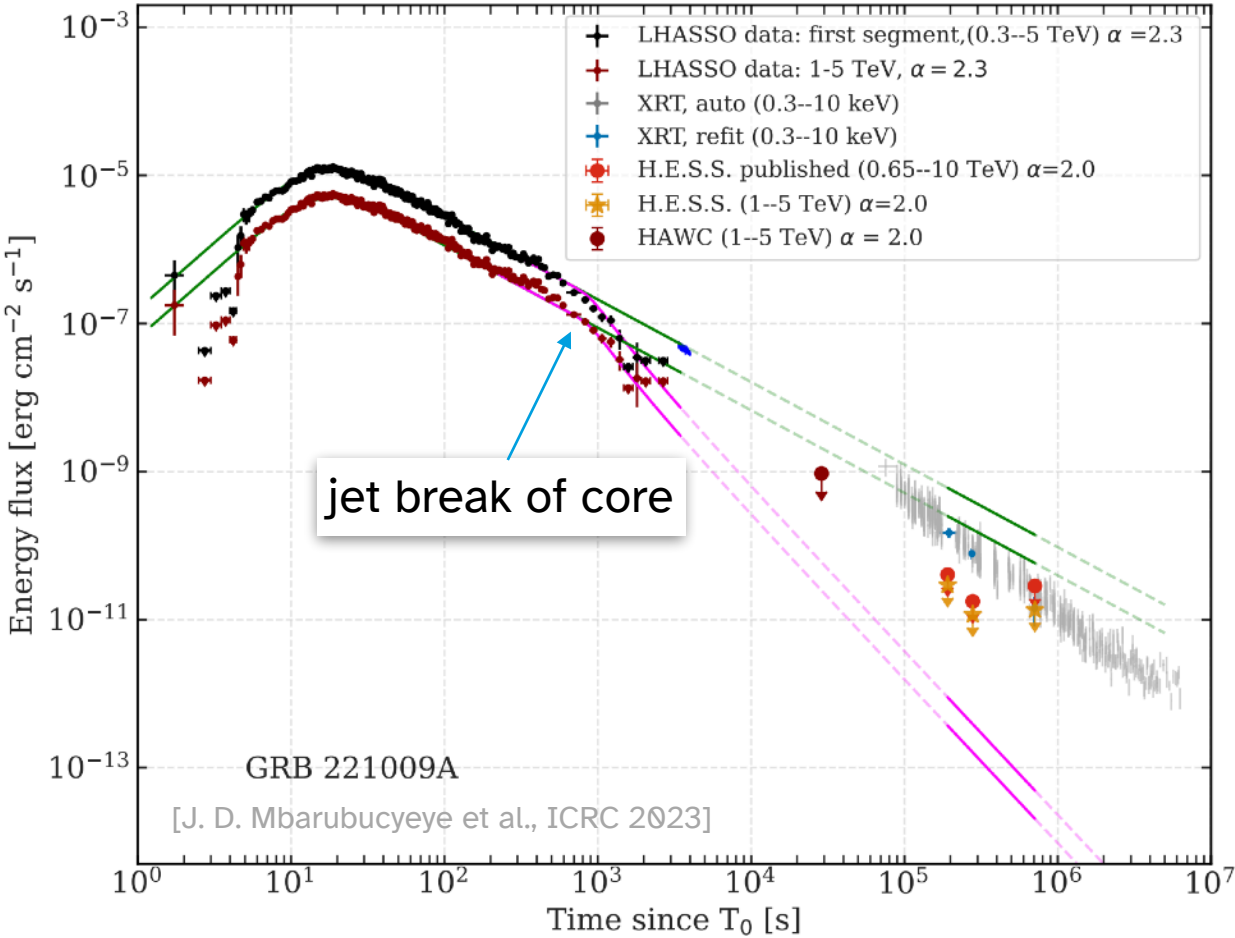


GRB 170817A was observed off-axis

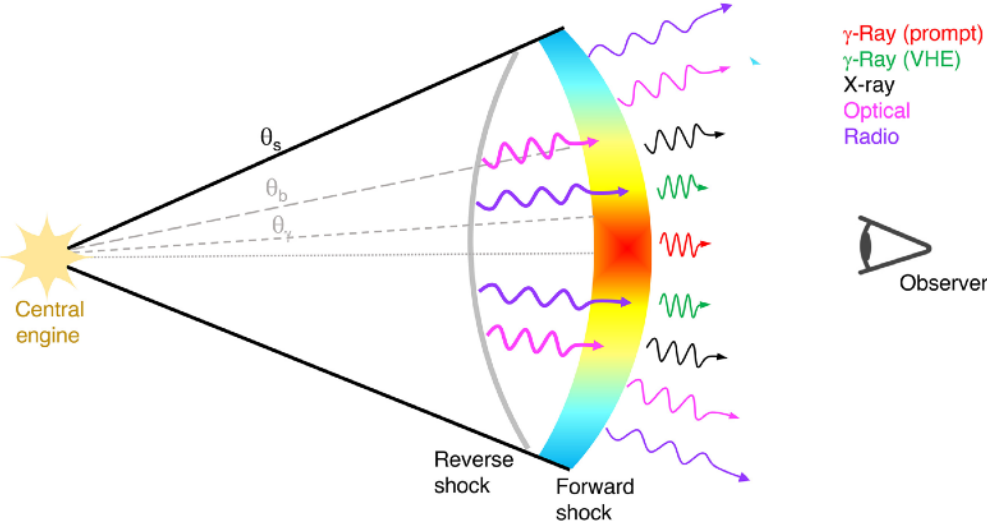
Reminder: GRB 221009A's jet break

looking down the core of a structured jet

The bigger MWL picture:



[B. O'Connor et al., Science Advances 9 (2023)]



Most likely a **structured jet**:

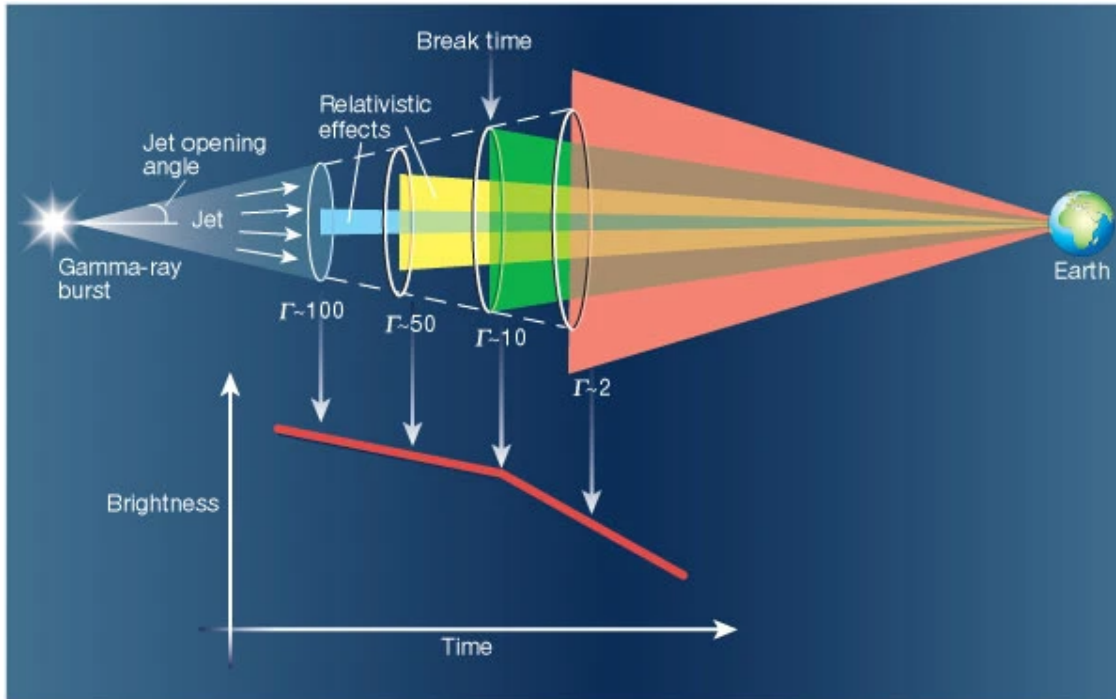
- narrow, high Γ core
- lower Γ wings

“standard” GRBs

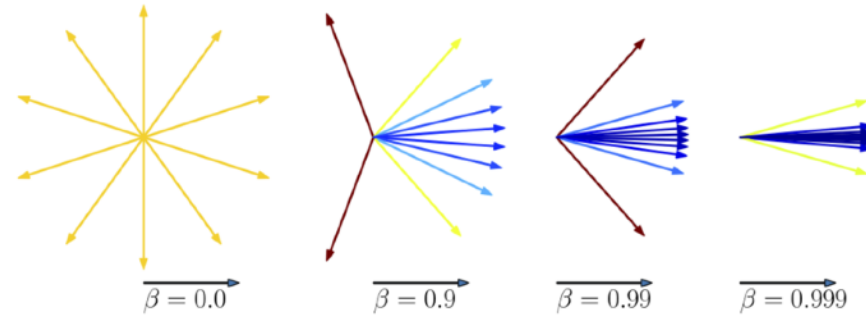
on-axis

GRB emission is relativistically beamed

[S. Woosley, Nature 414 (2001)]



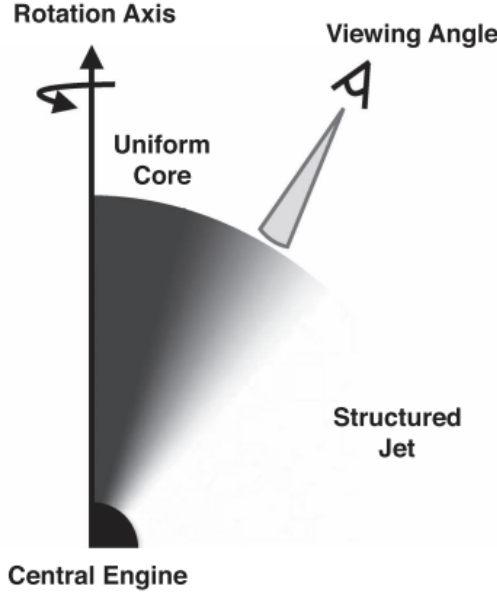
[D. C. Bailey]



For a standard on-axis GRB:
More of the emitting surface becomes visible at later times as the jet slows

GW170817 + GRB 170817A

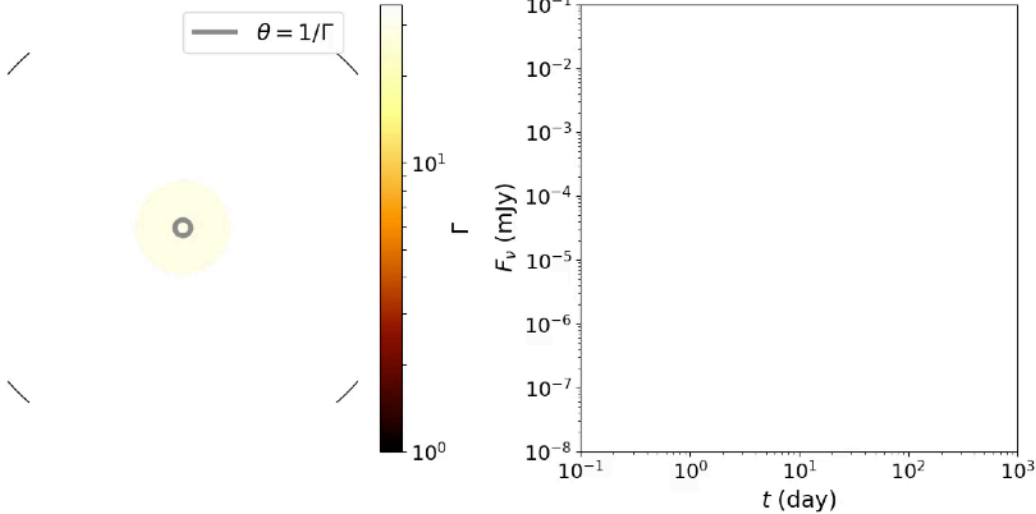
an off-axis GRB



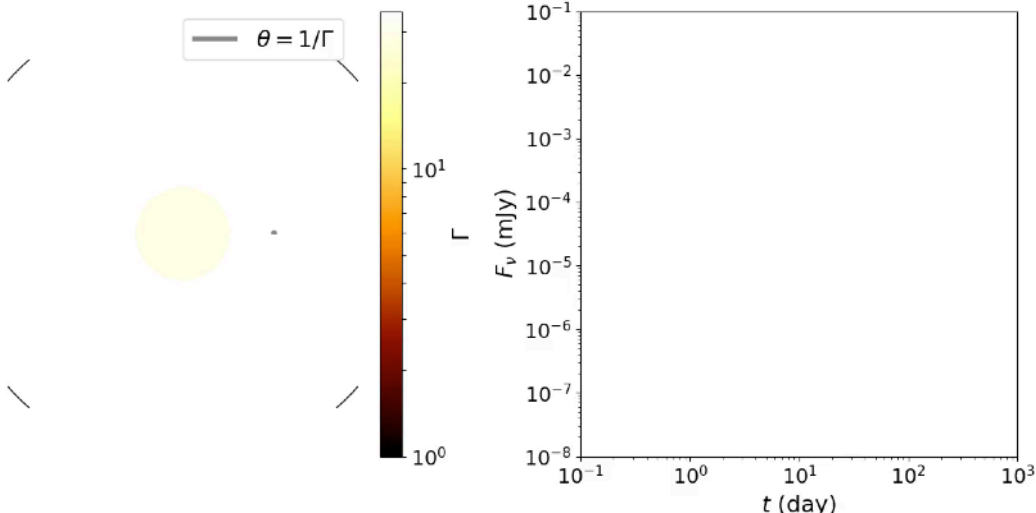
The afterglow of an off-axis GRB looks very different

simulations by Geoffrey Ryan, Perimeter Institute

on-axis:



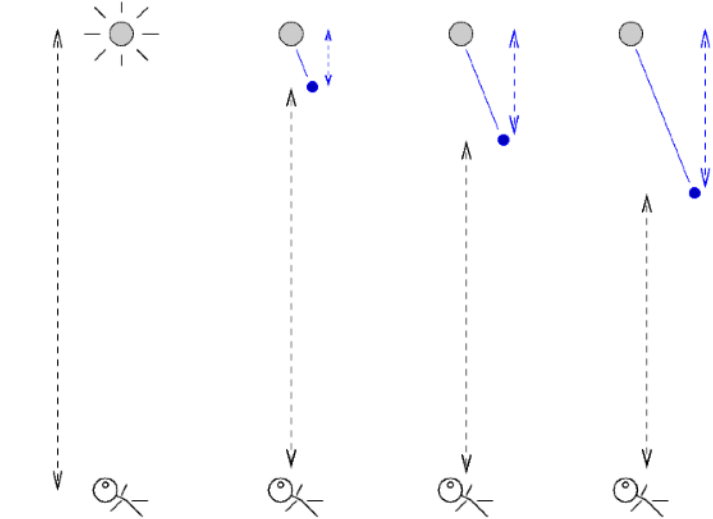
off-axis:



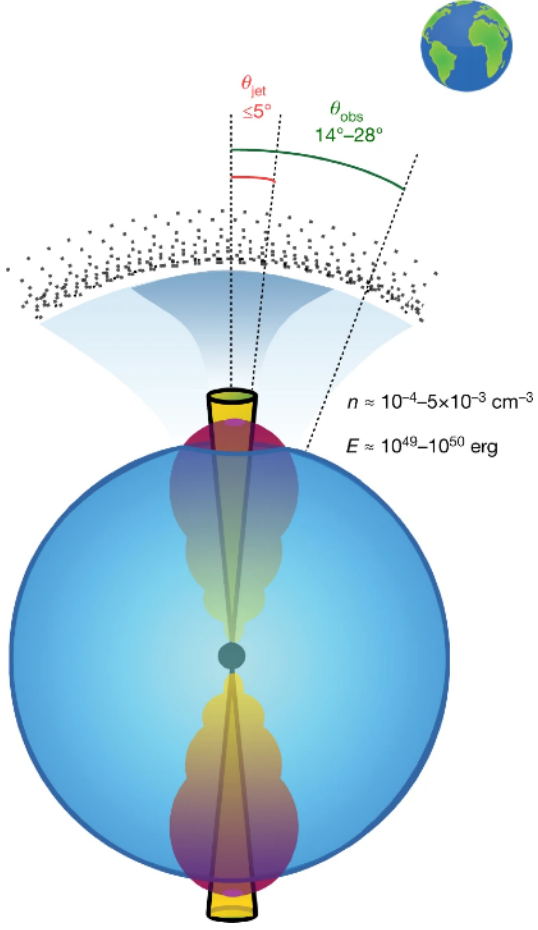
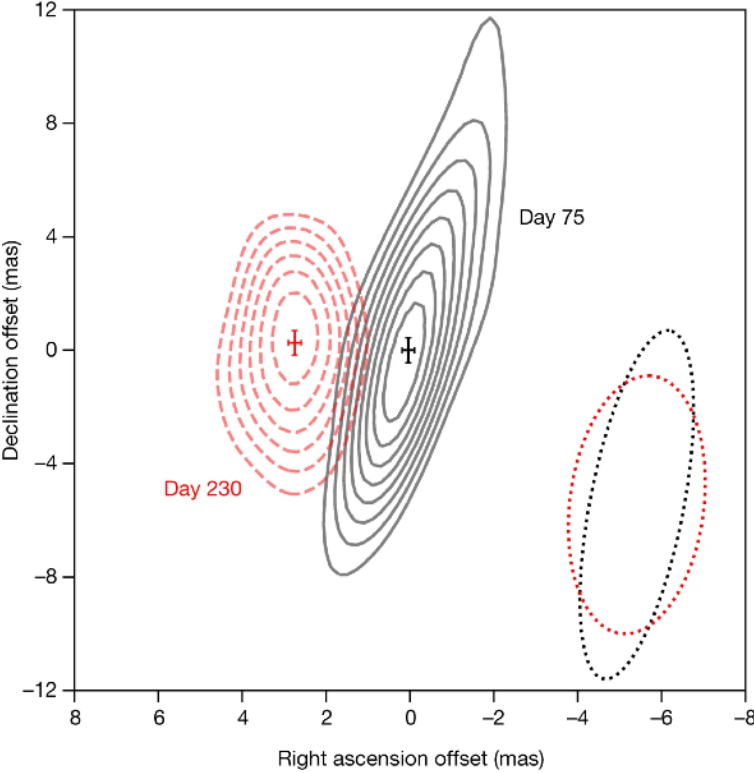
GW170817 + GRB 170817A

an off-axis GRB

Late-time radio images showed **superluminal motion**



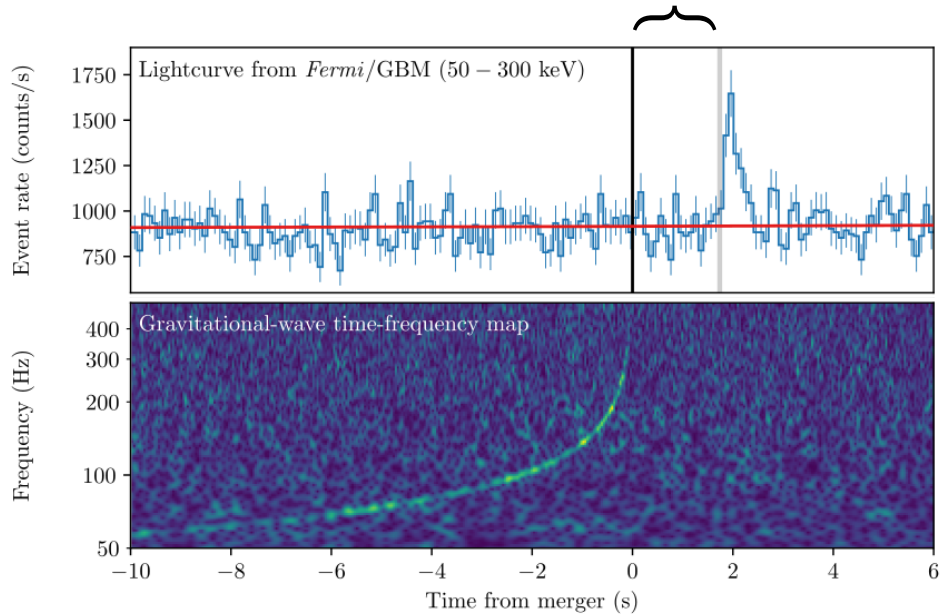
[K. P. Mooley et al., Nature 561 (2018)]



GW170817 + GRB 170817A

speed of light vs. speed of gravity

the two signals were detected 1.75s apart



modified from [B. P. Abbott et al., ApJL 848 (2017)]

This delay is (likely) because of the delay in producing gamma rays, but if we make some assumptions, we can calculate the relative difference between the speed of light and speed of gravity

$$\Delta v = v_{\text{GW}} - v_{\text{EM}}$$

$$-3 \times 10^{-15} \leq \frac{\Delta v}{v_{\text{EM}}} \leq +7 \times 10^{-16}$$

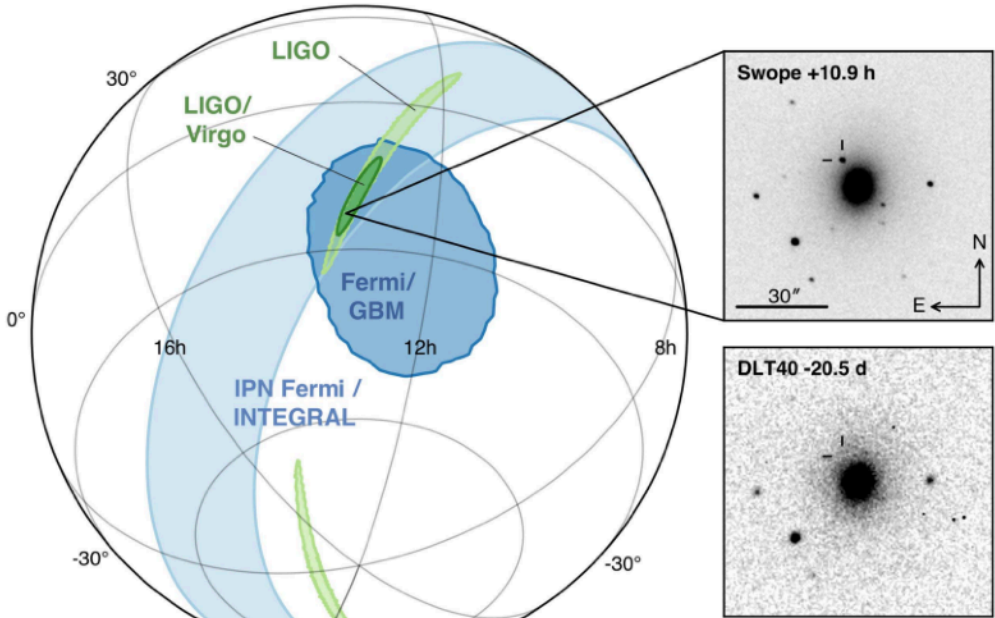
assume photons were emitted some (unreasonably) long time after the gravitational waves (here, 10s)

assume photons and gravitational waves were emitted simultaneously

IACT observations of GRB170817A

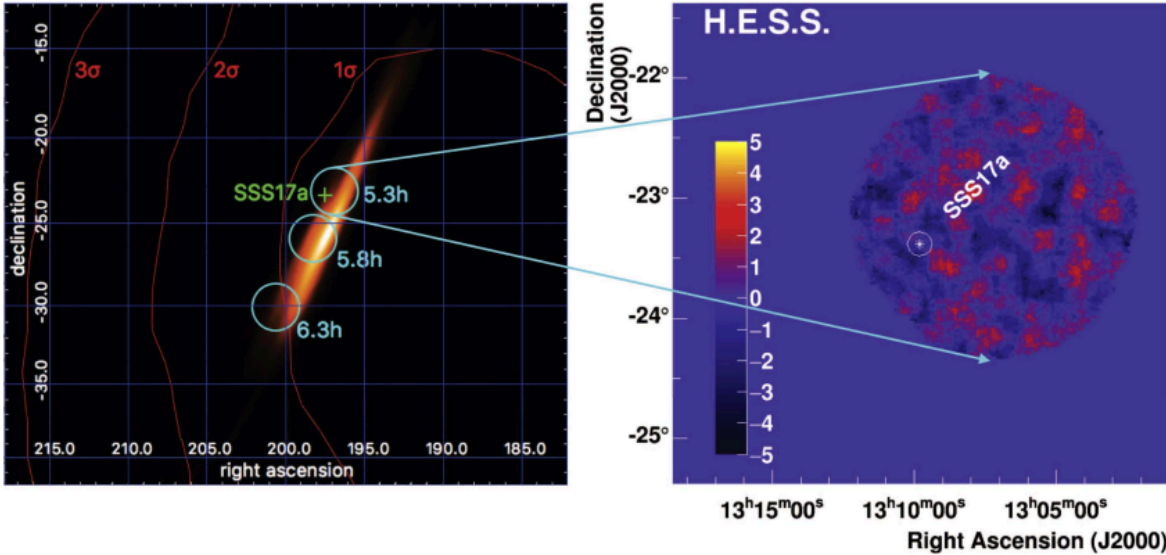
immediately after the merger

[B. P. Abbott et al., ApJL 848 (2017)]



gravitational-wave localization
gamma-ray burst localization

[H. Abdalla et al., ApJL 850 (2017)]



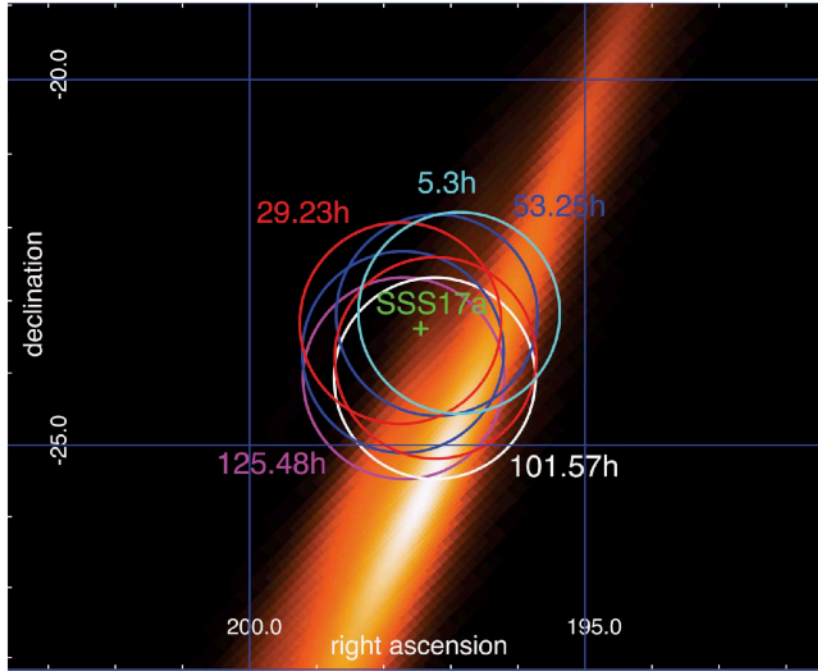
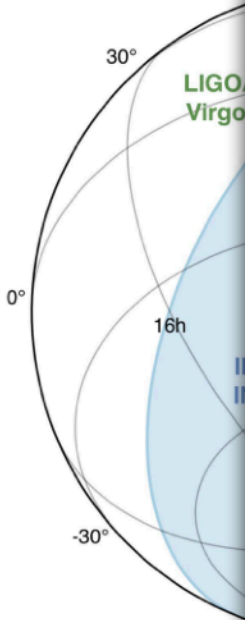
H.E.S.S. serendipitously observed the correct sky position in its first tile

IACT observations of GRB170817A

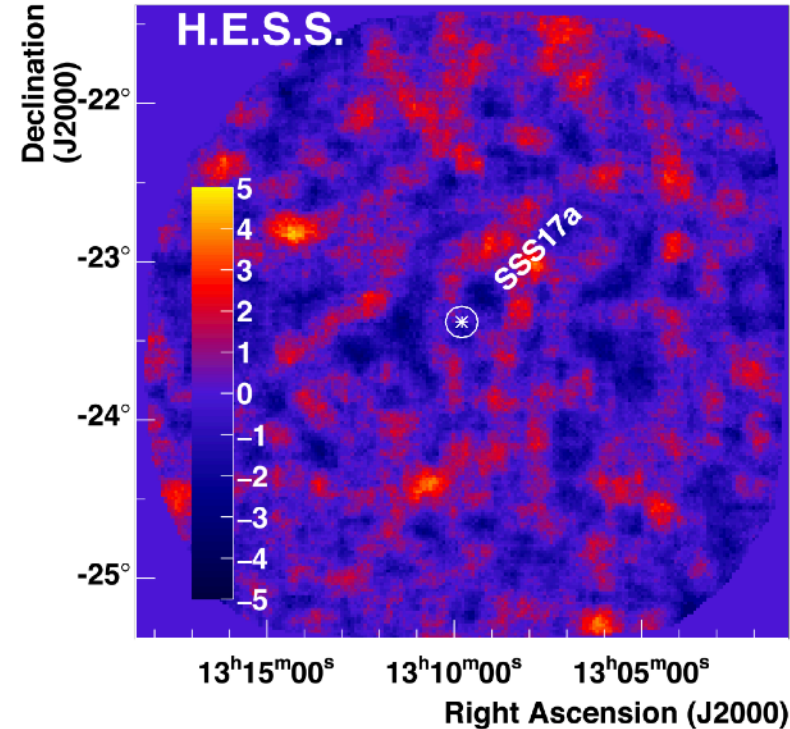
immediately after the merger

[H. Abdalla et al., ApJL 850 (2017)]

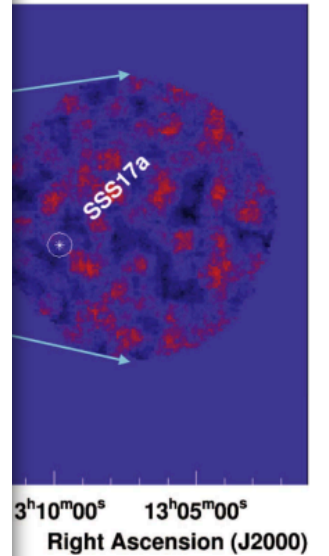
[B. P. Abbott et al.]



(a) SSS17a: H.E.S.S. pointings



(b) SSS17a: H.E.S.S. significance map



Right Ascension (J2000)

correct

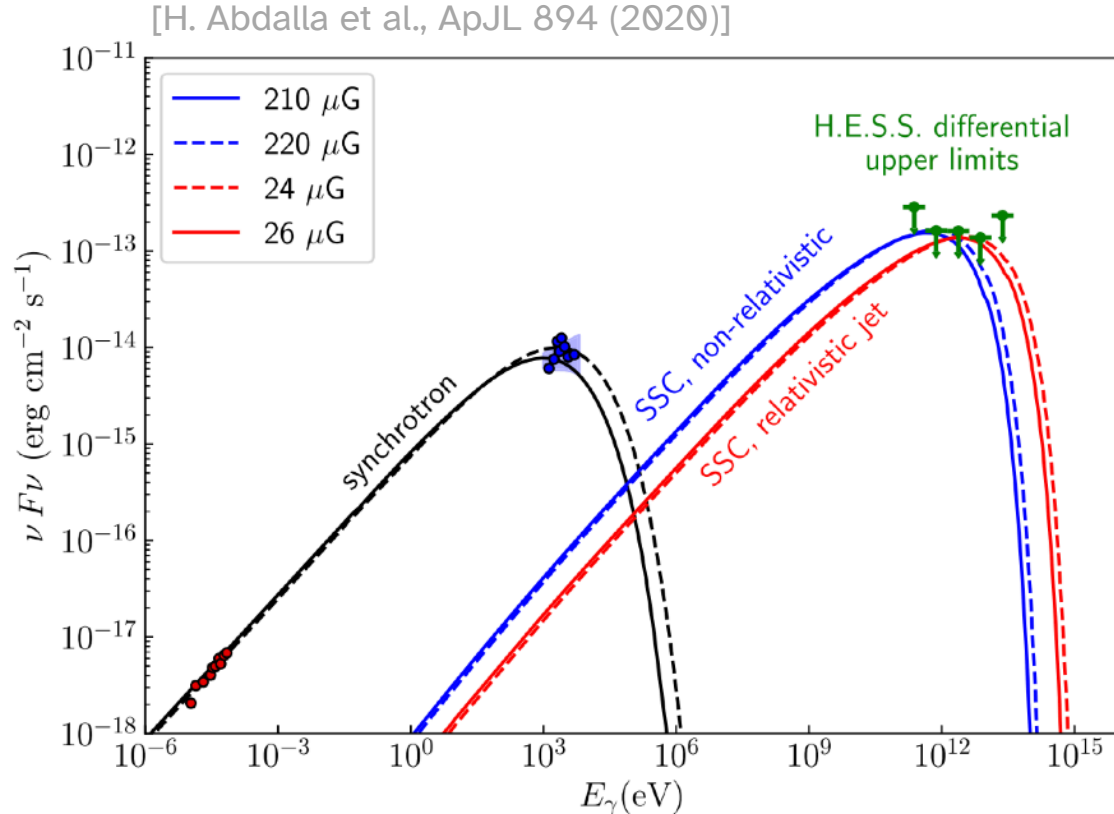
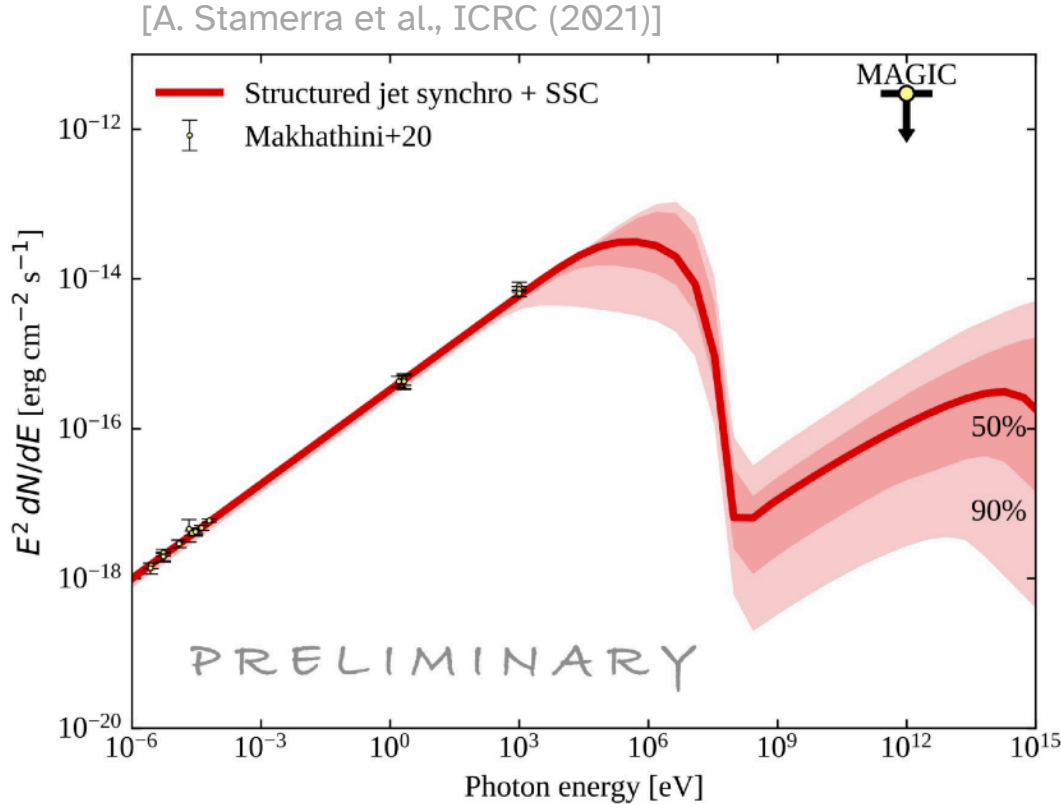
H.E.S.S. revisited the region over the next few days

(too far south for the other IACTs)

gravitational
gamma-ray

IACT observations of GRB170817A

deep in the afterglow phase



MAGIC and H.E.S.S. also observed the position at late times